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MODERN ASPECTS OF THE GEOLOGY OF NEW YORK CITY AND ENVIRONS

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MODERN ASPECTS OF THE GEOLOGY OF NEW YORK CITY AND ENVIRONS*

Conference Chairman
and
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KURT E. LOWE

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GROUND-WATER PROBLEMS IN THE NEW YORK CITY AREA

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Since the earliest colonial times, use of ground water for municipal and industrial supplies has grown steadily in the New York City area. Despite the fact that much of the water used in the city and its suburbs is derived from reservoirs, lakes, and streams, many municipalities and industries are entirely dependent on well-water supplies. The importance of the ground-water resource in metropolitan New York is shown by the fact that at least 300 to 400 million gallons daily (mgd) is pumped from wells within a radius of about 20 miles from Manhattan Island. In New York City alone, withdrawals of ground water are approximately 100 mgd.

Because geologic and hydrologic conditions vary widely from place to place, ground water is not equally abundant everywhere in the city and its suburbs. Some of the aquifers are unusually prolific and furnish large supplies to wells without causing any significant depletion of the ground-water resource. Other aquifers, however, have poor water-transmitting properties or are partly invaded by salty water, and furnish only small to moderate supplies of good water. It is the purpose of this paper to discuss several of the more serious ground-water problems that have developed in the metropolitan area and to outline briefly other ground-water conditions that may become troublesome in the future. The discussion will be limited to New York City and adjacent localities in New York and New Jersey that are commonly considered to be parts of the metropolitan area.

The New York City region is underlain by three major types of aquifers, (1) unconsolidated deposits of gravel, sand, and clay, (2) consolidated beds of sandstone and shale, and (3) crystalline igneous and metamorphic rocks. The unconsolidated deposits may be subdivided into two classifications: first, unsorted materials of glacial origin, such as the surficial deposits in most of the Bronx, Westchester, Manhattan, Staten Island, northern New Jersey, and northern Long Island; and, second, stratified deposits of glacial origin and older stratified beds of Cretaceous and Tertiary age. The stratified deposits occur extensively on Long Island, Staten Island, and the New Jersey coastal plain, and contain the largest supplies of ground water in the region.

The second major type of aquifer comprises the Triassic sandstones and shales of New Jersey and Rockland County. Yields of wells in these rocks range up to several hundred gallons per minute (gpm), in contrast to yields of as much as 1500 gpm from wells in the stratified sands and gravels. The third type of aquifer is the crystalline metamorphic rock that forms the basement complex beneath much of the New York City area. These rocks have no primary porosity, and transmit ground water only through joints and fractures. The distribution of the openings is irregular, and wells drilled into these rocks are successful only if they intersect enough water-bearing crevices. Most wells tapping the crystalline rocks yield less than 50 gpm.

Ground-water problems in the New York City area may be broken down into several principal categories. One of the most serious problems is the steady decline of ground-water levels in the vicinity of some heavily pumped installations. Such declines result from the withdrawal of water from wells at faster rates than it is replenished naturally, and ultimately can lead to depletion or contamination of the ground-water resource. Excessive pumping has occurred at several localities within the city limits and in the densely populated suburban areas of New Jersey and Long Island.

Another problem of increasing concern is encroachment of salty water into underground water-bearing formations in shoreline areas. This type of contamination has occurred on Long Island, Manhattan Island, and Staten Island, and also at various localities in New Jersey that are adjacent to tidal inlets and marshes.

Other ground-water problems in the region have arisen from increases in ground-water temperatures, contamination and pollution by domestic and industrial wastes, and flooding of subsurface structures caused by pronounced recoveries of ground-water levels.

The problem of overpumping of ground water is acute in the northeastern metropolitan counties of New Jersey, which contain almost three quarters of that state's population. Local ground-water resources are used virtually to capacity, and it has become necessary to import water from nearby areas of surplus. A major step toward easing the water-supply problem in northern New Jersey was taken when the voters of the state approved the water referendum carried on the ballot in November 1958. In addition to authorizing the construction of two large surface-water reservoirs, this referendum provides for a ten-year program of detailed studies to inventory the ground-water resources of the state. New Jersey officials are confident that the complete program will satisfy their immediate water requirements and will give a large impetus to industrial and municipal growth.

One of the most interesting ground-water problems in the metropolitan area is in Brooklyn, N. Y., where pumpage from wells has varied widely in recent decades. From the early 1900s to as recently as 1947, large quantities of ground water were pumped within the county for public supply. During that period, gross withdrawals for public consumption averaged about 23 mgd, and gross withdrawals for industrial use, about 36 mgd. Prior to 1933, little attention was given to the effects of this pumping on ground-water levels and water quality. In that year, however, a study was made of the ground-water situation; this revealed the existence of a critical ground-water problem. Contour maps prepared in connection with the study showed a crater or depression on the water table in the central part of the county extending to a depth of as much as 35 feet below sea level. In places, the outer boundary of this depression was at the shoreline; as a consequence, salt water from the nearby bays and river had begun to invade the aquifers.

During subsequent years, many wells were contaminated and the quality of the water served for public supply began to deteriorate. In the early 1940s, the chloride content of water from a few of the wells used for public supply was as high as 800 to 1,500 parts per million (ppm), in contrast to the normal 10 to 20 ppm in fresh ground water on Long Island. Complaints by users multiplied and, in June 1947, the city terminated the franchise of the only remaining water company in the county. Abandonment of the wells used for public supply reduced the total pumpage in Brooklyn from about 50 to 25 mgd. FIGURE 1 shows contours on the water table in 1903, before large-scale development of ground water took place. FIGURE 2 shows contours on the water table in June 1947, at the time pumpage was curtailed.

During the many years prior to the cutback in pumpage, when the water

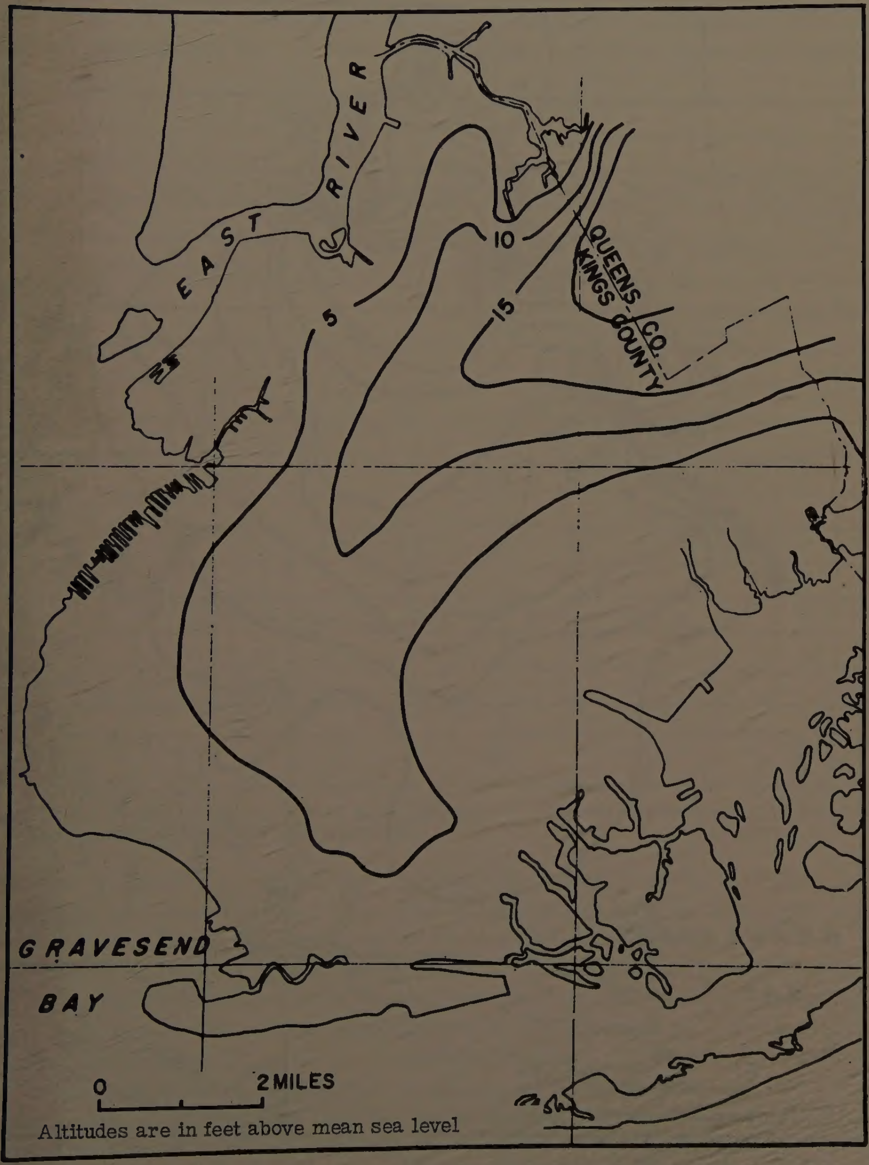
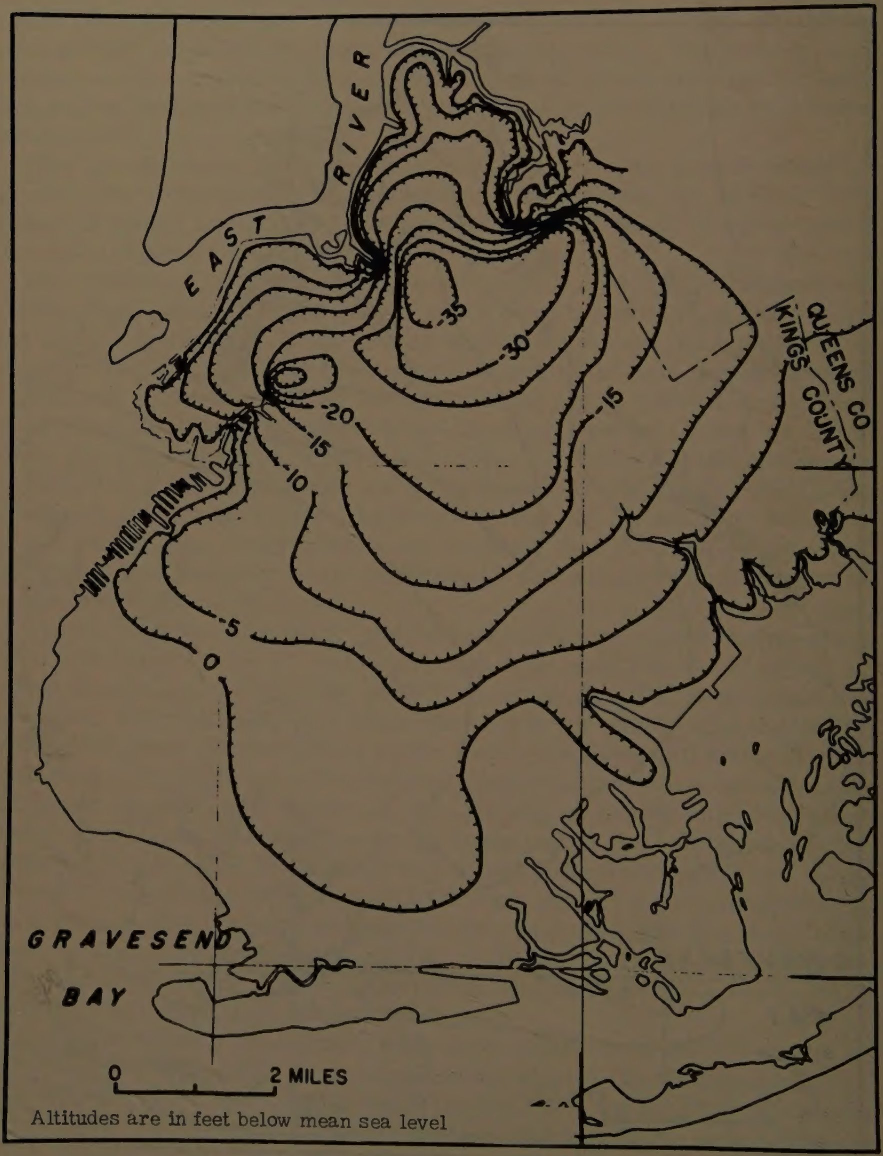


FIGURE 1. Contours on water table in Brooklyn, N. Y. in 1903.

table was at abnormally low levels, numerous deeply buried structures were built in the county. Subway lines and sub-basements of large buildings were excavated to depths below the original position of the water table in the early 1900s. Little or no effort was made to waterproof many of these structures, inasmuch as their designers did not anticipate a rise in ground-water levels. After 1947, however, the water table began to rise at comparatively rapid rates.



Altitudes are in feet below mean sea level

Figure 2. Contours on water table in Brooklyn, N. Y. in 1936.

By 1958, the depression in the central part of the county had been largely filled in, and the water table was at or slightly above sea level in most places.

This county-wide recovery of water levels has begun to cause damage in a few areas. The deepest subway cuts and the basements of several housing developments have been reached by the rising water, and it has become necessary to pump from some of these structures on an around-the-clock basis to prevent flooding. It seems likely that the water table will continue to rise to somewhat higher altitudes in the future, so that additional drainage problems of this type may occur. Figure 3, the hydrograph of an observation well in the north-central part of Brooklyn, shows that water levels in that area rose about 25 feet from 1947 to 1957. The average water level in unpumped portions of Long Island fell about two feet during the same interval.

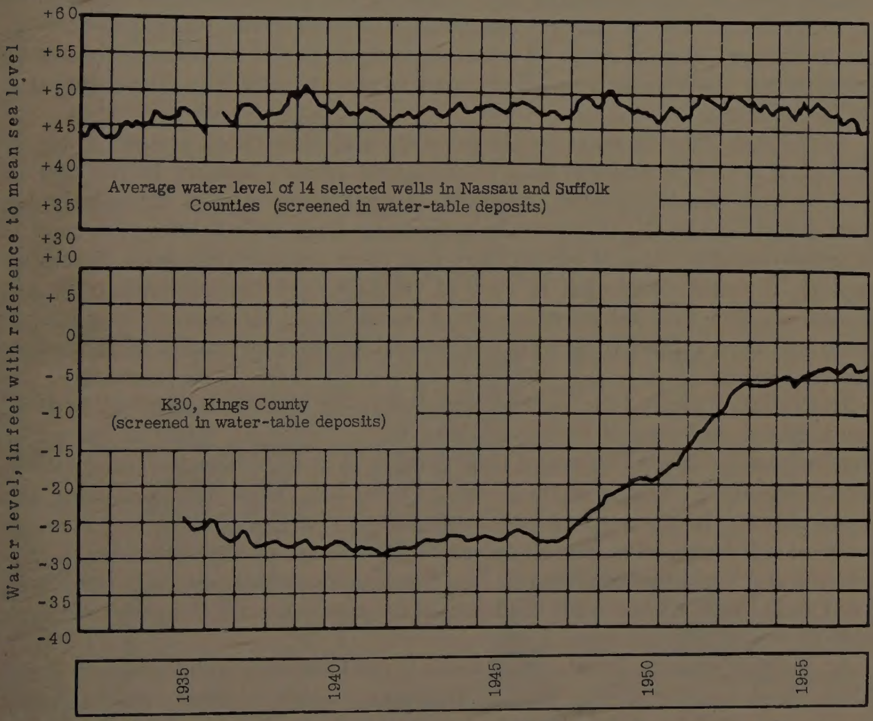


Figure 3. Hydrographs of well K30, Brooklyn, N. Y., and the average of 14 selected wells in Nassau and Suffolk counties, N. Y.

Another interesting ground-water condition in Brooklyn is the gradual rise in temperatures of well waters that has occurred in some parts of the county. On Long Island, the normal temperature of ground water at shallow depths ranges from about 52° to 55° F. throughout the year. In Brooklyn, however, some shallow wells presently yield water having a temperature above 80° F., and there is good evidence that the rise in temperatures is continuing. This condition has been brought about by the artificial recharging through wells of large amounts of warm water from cooling and air-conditioning systems.

In 1933, after the seriousness of the ground-water problem in Brooklyn had been brought to the attention of municipal and state officials, the New York State legislature passed a law designed to conserve the ground-water resources of Long Island. One of the regulations of this law requires that all ground water pumped on Long Island for cooling purposes in excess of 45 gpm be returned to the aquifer from which it is taken. Consequently, each theatre, store, or factory that uses ground water for cooling must install at least two wells—one for supply and the other to return the water underground after use. Inasmuch as the used water is considerably warmer than the pumped water, the net effect of the recharging is to warm up the ground water in the vicinity of the wells. This, of course, constitutes a vicious cycle, for warm water is not as efficient as cold water in a cooling system, and it becomes necessary to pump much more water at a greater cost to the operator to achieve the same cooling effect.

Fortunately, the increase in temperature and salinity of ground water in Brooklyn is now a problem only to industrial users. Farther to the east in Queens and Nassau counties, however, ground water is used extensively for public supply, and the threat of contamination from sea water in particular is of great concern. Use of ground water in these counties has been increasing rapidly in recent years and, in view of the fact that the aquifers are in hydraulic contact with salty surface-water bodies along the shores, considerable effort has been expended by state and federal agencies on studies of salt-water encroachment.

In Nassau County, the water-bearing deposits consist mainly of beds of sand, gravel, and clay of Pleistocene and Cretaceous age. Most of the water used for public supply is pumped from deep wells in the Magothy(?) formation, which extends to depths of from 600 to 1,000 feet below sea level along the south shore. In the extreme southwestern part of the county, an extensive body of salty ground water occupies the lower part of the formation. This saline water underlies the city of Long Beach and several towns on the Rockaway peninsula. A few wells used for public supply tap the Magothy within a mile or two of the salt-water body.

At the city of Long Beach, fresh water is pumped from wells screened in the Lloyd sand member of the Raritan formation, which underlies the Magothy and is separated from that formation by a clay bed only about 200 feet thick. At present, the United States Geological Survey, in cooperation with the Nassau County Department of Public Works and the New York State Water Power and Control Commission, is making an intensive investigation of the salt-water body to determine approximate rates of encroachment and the degree of danger of contamination of existing wells. FIGURE 4 shows the area underlain by salty water in southwestern Nassau County and also in other localities affected by salt-water encroachment in the metropolitan area.

Encroaching salt water is a problem to many other ground-water installations in the New York City region. At Newark, N. J., for example, numerous wells used for industrial purposes now yield water containing several thousand ppm of chloride, and many others face a threat of eventual contamination. Pumpage in the Newark area for general industrial purposes is more than 20 mgd. A large part of this withdrawal is from stratified Pleistocene sand and gravel which occupies a wide buried valley cut into the bedrock floor. Water levels in wells tapping these beds and the underlying sandstones and shales have declined severely in recent decades. Early records show that some wells terminated in these aquifers flowed at land surface; today, water levels are more than 200 feet below sea level in several places. The unconsolidated de-

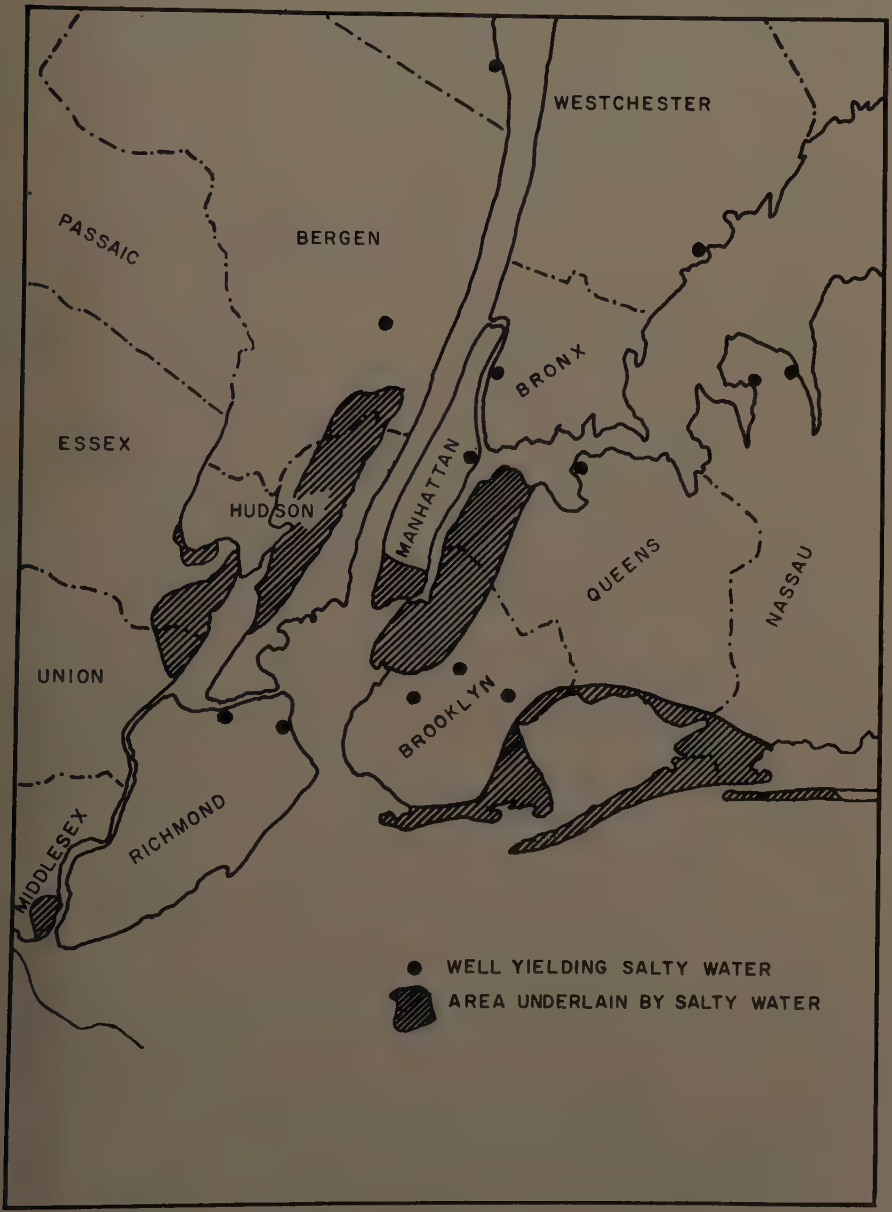


FIGURE 4. Occurrence of salty ground water in New York City area.

posits have been invaded by salt water that has percolated downward from the tidal reaches of the Passaic River, and wells near the point where the buried valley underlies the river yield water containing large amounts of chloride. FIGURE 5 shows the axis of the buried valley in Newark and isochlors based on data collected in 1942.

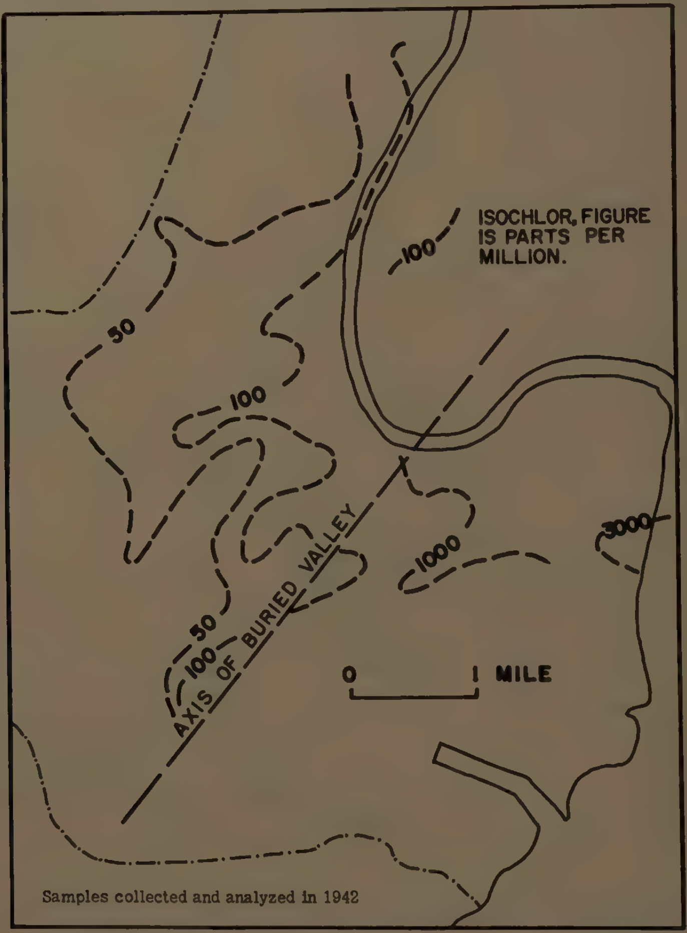

ISOCHLOR, FIGURE IS PARTS PER MILLION.
100
50
100
AXIS OF BURIED VALLEY
1000
3000
50
100
0
1 MILE
Samples collected and analyzed in 1942

FIGURE 5. Chloride concentrations in ground water at Newark, N. J.

In an effort to relieve this condition, water has been artificially recharged to the aquifers at times when the city's surface-water reservoirs overflow. Water that otherwise would have gone to waste is returned underground through wells and conserved for future use. This operation has also helped to lower ground-water temperatures, inasmuch as most of the water used in the recharging is obtained during the winter months.

Studies made in Newark during recharging experiments showed that ground-water levels in the immediate vicinity of the recharging wells rose appreciably. Even at considerable distances from these wells, water levels recovered noticeably. However, the highest water levels noted during the study were still about 50 feet below sea level; it would be necessary to expand the program greatly in order to halt further encroachment of salt water.

Artificial recharge is also being practiced at Perth Amboy, at the East Orange Water Works, at the Duhernal industrial water-supply facilities near Old Bridge, and at Princeton. The quantities of water introduced into the ground at each of these localities range from one to several mgd.

A majority of the industrial wells tapping the Farrington sand member of the Raritan formation in Perth Amboy and along the north shore of the Raritan River have been contaminated by encroaching salt water from the river and from Arthur Kill. Wells located in this area more than one mile inland from the salty streams have not been affected thus far, but encroachment undoubtedly is continuing, and the problem may become more serious in the future. The region south of the Raritan River between South Amboy and South River is partly protected against salt-water encroachment by a buried ridge of diabase that parallels the river. Where this ridge is traversed by the Washington Canal, however, salty water has invaded the shallow deposits.

The Perth Amboy Water Department was one of the first in New Jersey to recognize the value of artificial recharging and to construct works for replenishing ground water in one of its well fields. Originally, this recharging system consisted of a dam and pond on a small stream flowing through the well field. From time to time, the system has been enlarged until now an elaborate system of channels and basins spreads surface water over the area in which the wells are located. At times, practically the entire flow of the stream is used to recharge the aquifer.

Another suburban area in which artificial recharge is being practiced on a very large scale is Nassau County on Long Island, N. Y. At present, more than 400 individual pits or basins have been constructed in the county to return water to the ground. Each of these is an acre or more in size and receives water collected by storm sewers in the adjacent areas. This system has been highly successful in conserving millions of gallons of water that otherwise would have been wasted through sewers to tidewater. Studies of problems that have arisen in the operation of the basins are being carried on at an experimental recharge pit in Mineola, Nassau County.

Ground-water problems occur even on the island of Manhattan, where withdrawals from wells for industrial and cooling purposes average about 6 mgd. In most of Manhattan, bedrock is at relatively shallow depths, and groundwater supplies are limited. In the southern and north-central parts of the island, however, relatively deep depressions are found in the rock surface. The bedrock surface is as much as 250 feet below sea level in southern Manhattan and as much as 175 feet below sea level in the north-central part. The northerly depression follows a major fault zone trending northwest across the island from 96th Street and the East River to about 125th Street and the Hudson River. The southerly depression extends south from about 14th Street. Both depressions are filled with glacial deposits that contain most of the available ground water on the island. Of 58 recorded wells in the southern depression, 47 have an average yield of 150 gpm. Of the wells in the north-central depression, three have an average yield of 60 gpm.

Salt water from the rivers surrounding Manhattan Island has invaded the unconsolidated deposits in both of the depressions. More than half of the wells south of 14th Street yield water containing over 100 ppm of chlorides, and a few of these wells yield water containing more than 10,000 ppm.

Natural recharge from precipitation is probably negligible in most of Manhattan, owing to the sealing of the land surface by pavements and buildings. Nevertheless, fresh ground water is present in relatively large quantities in many parts of the island. It is believed that much of this fresh water can be attributed to leakage from buried water mains and sewers. Evidence of the importance of underground leakage is given by the fact that in 1950, the Bureau of Water Supply located and stopped leaks totalling 6.5 mgd. Total groundwater pumpage in Manhattan at that time was estimated to be about 5 mgd.

An interesting feature of the ground-water body in southern Manhattan is its unusually high temperature. Available records show that well-water temperatures in that area average more than 10 degrees above normal. Unlike the Brooklyn condition, however, which developed from artificial recharge of warm water, the Manhattan temperature condition is thought to be largely a result of heat loss from buried steam pipes, basements, and subways.

One ever-present ground-water problem in the metropolitan area is the flooding of excavations during construction work. Contractors for subways and other buried structures often encounter unusually large ground-water flows and must install extensive networks of wells to dewater excavations. Recently, during installation of foundations for a new office building in lower Manhattan, large quantities of subsurface water began to pour into the cut, apparently through a buried former stream channel. The engineers on the project were certain that they were dealing with a natural ground-water phenomenon, and carried out an extensive grouting and waterproofing operation to block the inflow. Later, to their chagrin, they discovered that the water was coming from the air-conditioning system of a nearby building. Many years before, when the air-conditioning equipment was being installed, someone noticed an abandoned pipe protruding from the basement floor and decided to dispose of the waste water by injecting it into the pipe. The other end of the pipe terminated in the old stream channel, which formed a perfect conduit for transporting the water into the new excavation. Although this was not a natural ground-water condition, the contractor dealt with it as if it had been. Many other deep foundations in the city have been affected in a similar manner, some by normal ground-water inflows and others by flooding from man-made sources.

Another ground-water problem that has recently begun to trouble some suburban areas is the underground migration of synthetic detergents to wells used for water supply. Today, a wide variety of detergents is in everyday use for household washing purposes, and large quantities of these cleansing agents are put into the ground through individual home cesspools and septic tanks. Unlike old-fashioned soaps, synthetic detergents do not deteriorate or stabilize to less objectionable compounds, and consequently remain in the ground water in a more or less unaltered state. Thus, in some areas where detergents have migrated from cesspools or septic tanks, soap suds have shown up in water from nearby shallow wells. This problem has proved especially troublesome in parts of Suffolk County, Long Island, and is presently under investigation by the county authorities. A measure of the seriousness of such contamination is given by the results of a study recently made by the Suffolk County Department of Health, which showed that approximately 15.6 tons of synthetic detergents were being discharged into cesspools each year in a typical 70-acre tract containing 300 families.

The ground-water problems that have been discussed here are by no means the only ones in the metropolitan area, but have been selected as typical of the difficulties in many parts of the city and its suburbs. The basic reason why many of these conditions have reached serious proportions is that too little attention was given to the ground-water resource during the early stages of its development. Ground water, like all natural resources, must be developed on the basis of long-term conservation. Future needs as well as present demands must be considered in planning large withdrawals, and pumping patterns and spacing of production wells should be established only after detailed geologic and hydrologic information has been obtained. With proper management, our ground-water resources can last indefinitely, and the vexing and costly problems that beset some localities will not recur.

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GEOLOGY AND GROUND-WATER SUPPLIES OF THE SOUTH-SHORE BEACHES OF LONG ISLAND, N. Y.*

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Introduction

The south-shore beaches of Long Island are unique areas both geologically and hydrologically. Geologically, the sediments beneath the beaches are those farthest downdip that can be studied on Long Island. In these areas are likely to be found new formations that are not found inland, facies changes in aquifers that extend inland, and intertonguing of marine and continental sediments. Hydrologically, the aquifers beneath the beaches may be invaded by sea water, or the fresh-salt water interface may lie close to shore and influence the pattern of movement of the fresh water.

A large permanent population resides on the westernmost beaches, which are well known as summer recreational areas. Construction of new roads and bridges on Long Island has intensified interest in development of the beaches of eastern Long Island as resort areas. Availability of water is a key factor in these plans. At the present time the total pumpage from wells on the beaches averages about 7 million gallons per day (mgd), but it is as much as 10 to 12 mgd during peak consumption in the summer months.

The United States Geological Survey has investigated ground-water conditions in parts of these areas from time to time in cooperation with the New York State Water Power and Control Commission, the Nassau County Department of Public Works, the Suffolk County Water Authority, and the Suffolk County Board of Supervisors. In most of the investigations the studies of the beach areas were part of a larger areal investigation, and little detailed work was done on the beaches themselves. The present paper summarizes current concepts of the geologic and hydrologic relations of the formations beneath the beaches.

Location and Topography

The south-shore beaches of Long Island extend for about 120 miles from Seagate in western Kings County to Montauk Point in eastern Suffolk County (FIGURE 1). The beaches are of three principal types: (1) border beaches attached to the Island proper, (2) normal and recurved spits of relatively short extent attached at one end to the island, and (3) offshore bars or barrier beaches extending for many miles, separated from the island proper by shallow bays up to about 5 miles in width. The beaches generally are less than half a mile wide; they are breached in a few places by artificially deepened inlets. The natural surface consists of scattered dunes separated by shallow depressions, and the total relief seldom exceeds about 25 feet. The surface of the highly developed beaches of western Long Island has been leveled, and the shore line has been extended and improved by artificial fill largely composed of sand

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* Publication authorized by the Director, United States Geological Survey, Washington, D. C.

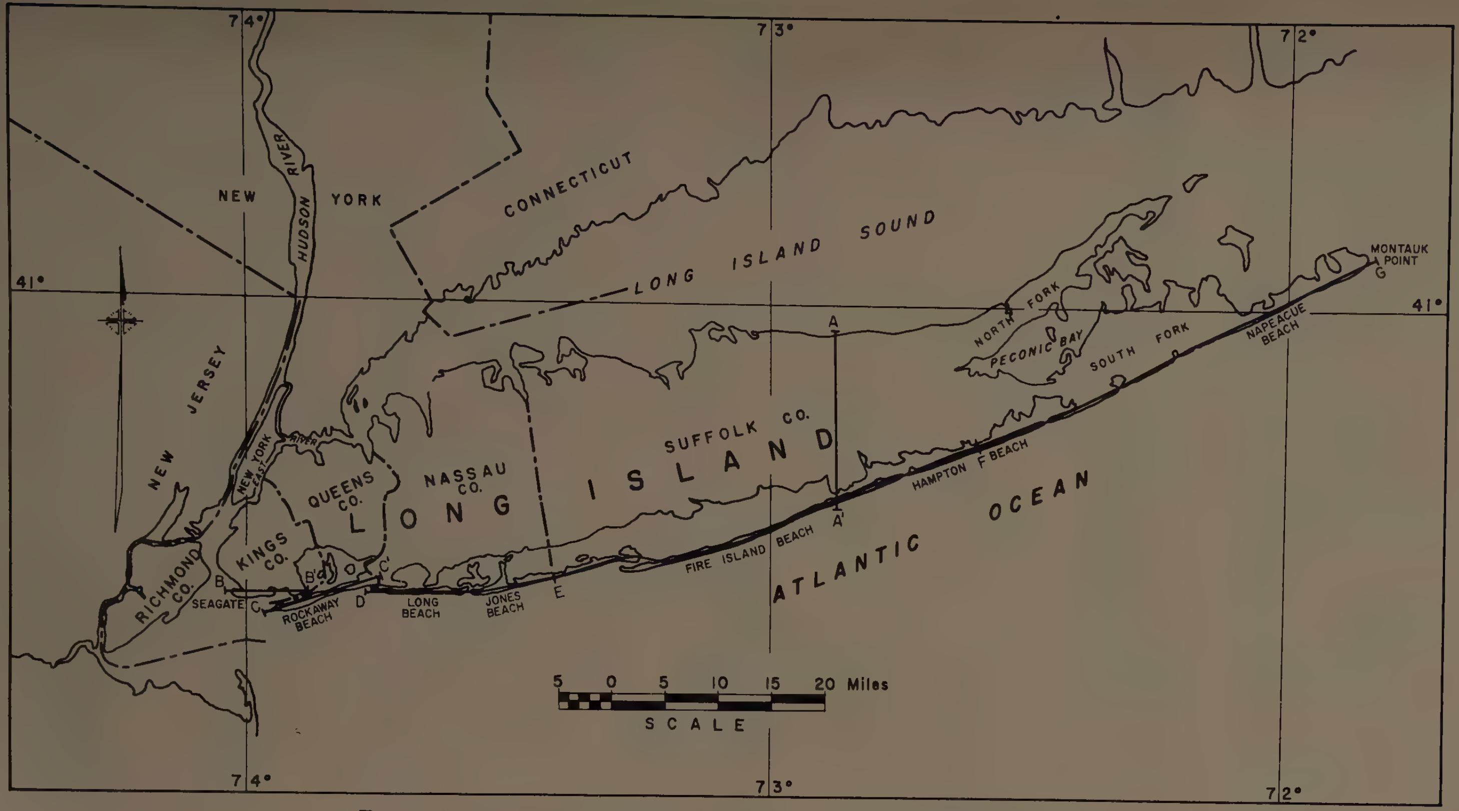

FIGURE 1. Map of Long Island, N. Y., showing location of geologic sections.

dredged from nearby bays. At Montauk Point in extreme eastern Suffolk County, steep cliffs of the Ronkonkoma terminal moraine rise abruptly in back of the narrow beaches to altitudes of about 70 feet above sea level. The bay bottom on the north side of the beaches deepens gradually toward the center of the bays or toward artificial channels. Natural water depths in the bays seldom exceed 10 feet, but artificially deepened channels are as much as 40

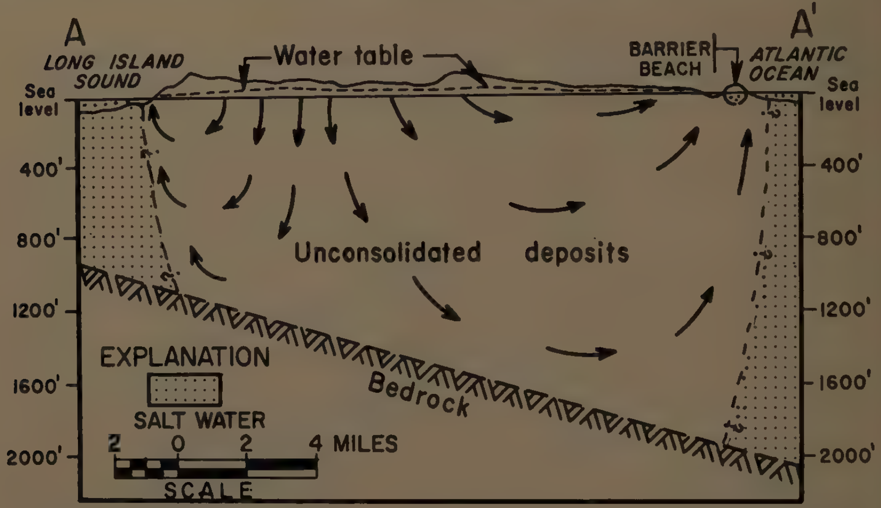

FIGURE 2. Generalized section A-A′ showing pattern of movement of fresh ground water in central Suffolk County.

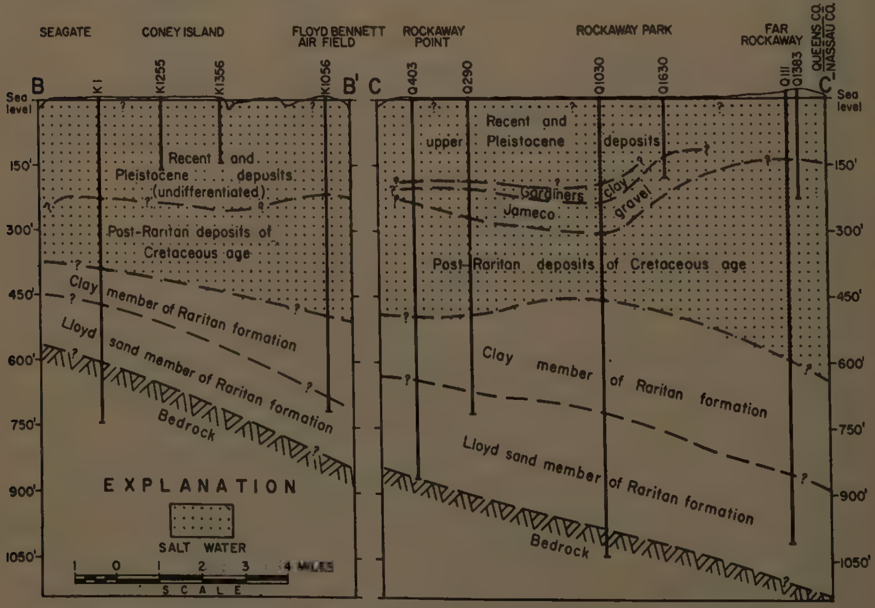
SEAGATE
CONEY ISLAND
FLOYD BENNETT AIR FIELD
ROCKAWAY POINT
ROCKAWAY PARK
FAR ROCKAWAY
QUEENS CO.
NASSAU CO.
B
K1
K1255
K1356
K1056
B'
C
Q403
Q290
Q1030
Q1630
Q111
Q1383
C'
Sea level
150'
300'
450'
600'
750'
900'
1050'
Recent and Pleistocene deposits (undifferentiated)
Post-Raritan deposits of Cretaceous age
Clay member of Raritan formation
Lloyd sand member of Raritan formation
Bedrock
Recent and upper Pleistocene deposits
Gardiners clay
Jameco gravel
Post-Raritan deposits of Cretaceous age
Clay member of Raritan formation
Lloyd sand member of Raritan formation
Bedrock
EXPLANATION
SALT WATER
1 0 1 2 3 4 MILES
SCALE

FIGURE 3. Section B-B′, Kings County, and section C-C′, Queens County.

feet deep. On the ocean side of the beaches the sea bottom slopes gradually, and water depths within a mile of the shore rarely exceed 50 feet.

General Geology

The geology of Long Island has been described in detail by Fuller (1914), Veatch (1906), Suter *et al.* (1949), and by others. The geologic units delineated in cross sections on FIGURES 3, 4, 5, and 6 and the descriptions given below are based partly on these and other reports and partly on interpretation of unpublished data from the files of the U. S. Geological Survey and the New York State Water Power and Control Commission. A summary of the stratigraphy is given in TABLE 1.

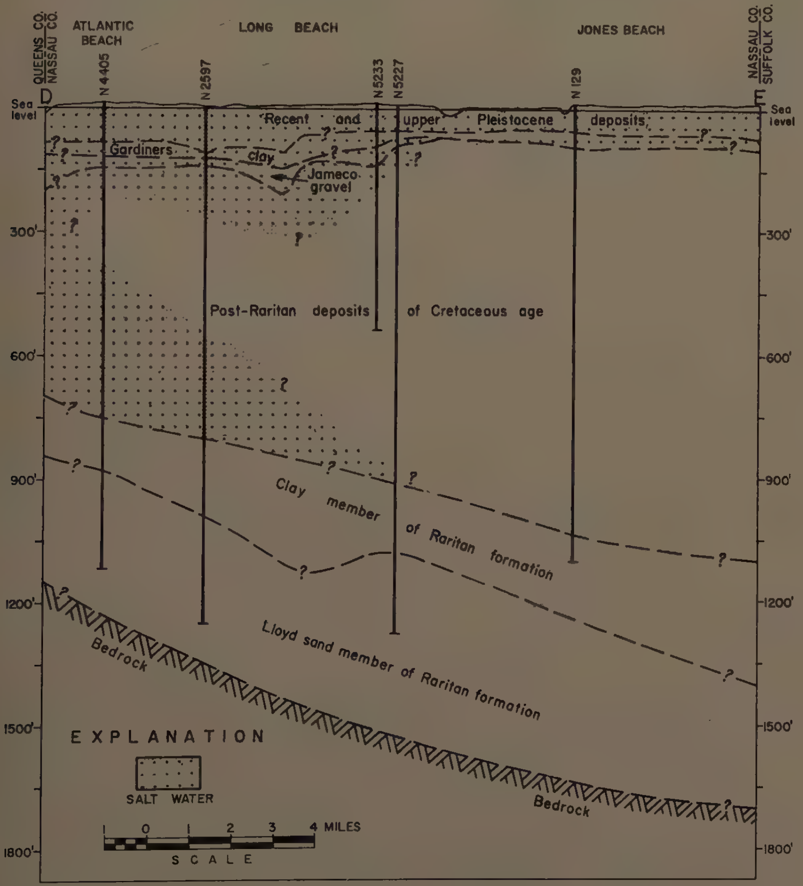

FIGURE 4. Section D-E, Nassau County. After Perlmutter *et al.*, 1957.

Unconsolidated beds of sand, gravel, silt, and clay ranging from about 500 to 1,900 feet in thickness rest on a seaward-sloping bedrock surface. The crystalline bedrock is of Pre-Cambrian age. Immediately above the bedrock are formations of Late Cretaceous age, overlain by deposits of Quaternary

(Pleistocene and Recent) age. In this paper the deposits of Cretaceous age are divided into the Raritan formation, consisting of the Lloyd sand member and an overlying clay member, and post-Raritan deposits of Cretaceous age. The latter unit in previous reports (Thompson *et al.*, 1937; Suter *et al.*, 1949)

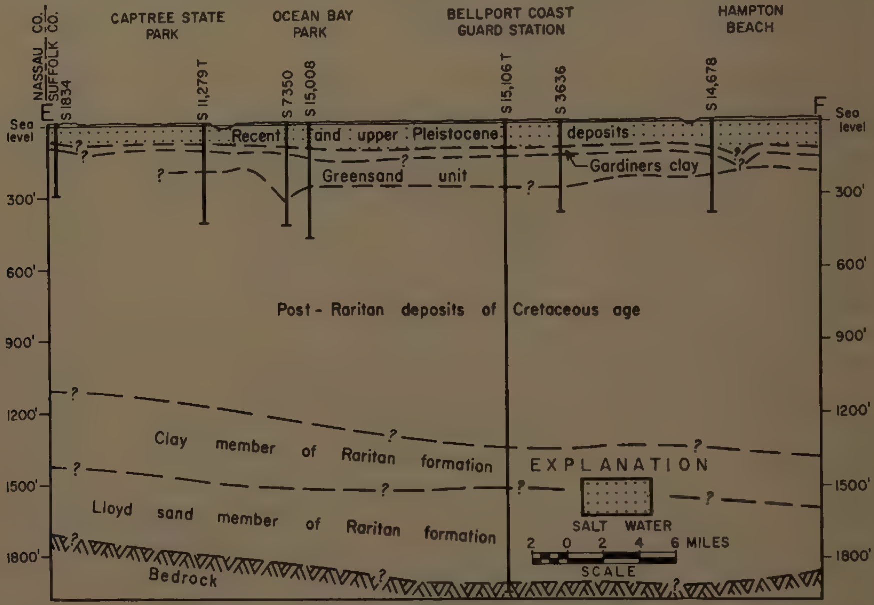

FIGURE 5. Section E-F, western Suffolk County.

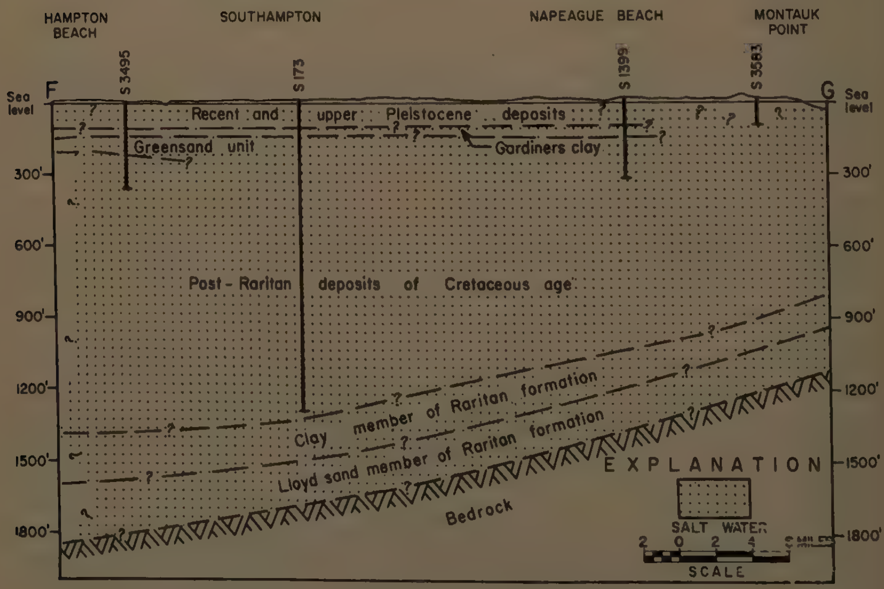

FIGURE 6. Section F-G, eastern Suffolk County.

TABLE 1

STRATIGRAPHIC SECTION FOR THE SOUTH-SHORE BEACHES, LONG ISLAND, N. Y.

System	Series	Geologic formation or unit	Thickness (feet)	Lithologic properties	Water-bearing properties
Quaternary	Recent	Recent deposits	50±	Beach and dune sand and gravel, commonly containing shells. Some thin layers of clay.	Permeable deposits yield small supplies of fresh water from scattered lenses. Contain chiefly salt water in lower part.
	Pleistocene	Upper Pleistocene deposits	40–150±	Brown and gray sand and gravel and some thin beds of clay.	Highly permeable; contain chiefly salt water. Individual wells yield 50 to 1,000 gpm.
		—Unconformity?—			
		Gardiners clay	0–50±	Gray-green silt and clay, some glauconite; in few places predominantly sand; Foraminifera and diatoms common.	Permeability generally low; extensive confining unit.
		—Unconformity?—			
		Jameco gravel	0–100±	Gray and gray-brown coarse sand and gravel. Contains abundant erratic rocks and minerals in some places. Largely restricted to western area.	Highly permeable; generally yields salt water.
		—Unconformity—			
Cretaceous	Upper Cretaceous	Greensand unit	0–200±	Green and gray clay and sandy clay, glauconitic; contains shell fragments and Foraminifera.	Permeability relatively low; not an aquifer.
		Post-Raritan deposits	150–1200±	Gray fine to medium sand mixed with silt and clay, some beds of coarse sand and gravel and solid clay; lignite abundant.	Include several permeable water-bearing zones; yield 200 to 1,200 gpm to individual wells; some wells flow. Water fresh in central part of area but salty in eastern and western parts.
		—Unconformity—			
		Raritan formation Clay member	75–350±	Gray, white, red, and black silt and clay and some lenses of sand and gravel.	Permeability relatively low; an extensive confining unit.
		Lloyd sand member	120–400±	Gray sand and gravel and some beds of red, white, and gray clay and silt.	Good aquifer; permeable zones yield 300 to 2,000 gpm to individual wells. Water fresh in most places but salty in eastern Suffolk County.
		—Unconformity—			
Precambrian		Crystalline rocks	—	Granite and granite gneiss.	Permeability low; not an aquifer.

has been referred to as the Magothy(?) formation. The question mark signified that the unit probably included several undifferentiated Cretaceous formations in addition to the Magothy.

Paleontologic evidence given below suggests the presence of Cretaceous formations younger than the Magothy which probably correlate in age with the Navarro group of Texas. The nomenclature of the several Quaternary units described below is the same as that used in recent reports of the Geological Survey.

Cretaceous deposits. The Cretaceous deposits are almost entirely nonmarine. The Lloyd sand member of the Raritan formation consists of gray sand and gravel and some beds of white and gray clay and silt. The overlying clay member is composed largely of gray, white, red, and black silt and clay and some lenses of sand and gravel. The post-Raritan deposits of Cretaceous age have a wide range in lithology. Immediately above the Raritan formation they consist of gray coarse sand and gravel mixed with some clay. Above the gravelly zone are chiefly thick beds and lenses of fine to medium sand, some mixed with clay and silt and some relatively clay-free. Beds of clay 5 to 40 feet thick occur at various depths. Lignite is common as disseminated particles or in layers several feet thick, and spores and pollen are abundant in some zones. Studies are in progress to determine the use of plant fossils as correlation tools, but no reports have been published.

In much of Suffolk County the uppermost unit of Cretaceous age is a fossiliferous glauconitic sandy clay that occurs from about 100 to 300 feet below sea level and is 50 to 200 feet thick. It is referred to as the greensand unit in this report, and is roughly delineated on parts of FIGURES 5 and 6. The northern limit of the unit is not known precisely, but it is believed to lie close to the shore line on the north side of the bays, and in a few places it extends inland for short distances. Foraminifera tentatively considered to be of Late Cretaceous age and possibly equivalent in age to fossils found in the Navarro group of Texas and in the Monmouth group of New Jersey have been found in wells S7350 (Fire Island Beach Club, depth 270 to 310 feet), S11,279T (Captree State Park, depth 104 to 106 feet) and S15,106T (Bellport Coast Guard Station, depths 162 to 184 feet, 205 to 228 feet, and 263 to 285 feet). Detailed studies are now in progress (M. R. Todd, United States Geological Survey, written communication, October 13, 1958) to identify the Foraminifera and to determine the age of the beds. Among the difficulties involved in correlating the formations from microfossils are the small number of wells for which samples are available and the contamination of samples typical of rotary drill holes. Seventeen identified Foraminifera from well S7350 are listed in TABLE 2. The boundaries of the greensand unit shown on FIGURES 5 and 6 are based largely on correlations made from drillers' logs and are considered tentative, as in many drillers' logs it is difficult to distinguish the Gardiners clay from the greensand unit. Furthermore, it is conceivable that some of the uppermost beds included in the greensand unit may be of early Tertiary age, although there is little evidence from preliminary micropaleontological studies to substantiate such an assumption.

Quaternary deposits. The Pleistocene deposits are divided from oldest to youngest into the Jameco gravel, the Gardiners clay, and the upper Pleistocene deposits. The Jameco gravel is an outwash deposit of early Pleistocene age, composed of gray and gray-brown coarse sand and gravel and containing abundant particles of erratic rocks and minerals in some places. It extends from near Long Beach, Nassau County, westward to Kings County, and probably is present also in part of extreme eastern Suffolk County, but there the data are few and the extent of the formation is uncertain. The Gardiners clay is a gray-green silt and clay containing some lenses of sand that overlies the Jameco gravel and Cretaceous deposits. In some places the clay contains glauconite and an abundance of shells and Foraminifera (MacClintock and Richards, 1936; Weiss, 1954). It is distributed extensively along the south shore, and generally occurs at depths of about 80 to 130 feet below sea level, but in some places it is somewhat higher or lower than this range. In Kings and Queens counties the Gardiners clay may be extensively eroded. In general, the boundaries of these units in the shore line areas of Kings and Queens counties are not well delineated because of lack of data.

TABLE 2

FORAMINIFERA OF LATE CRETACEOUS AGE FROM DEPTH OF 270 TO 310 FEET IN WELL S7350*

(1) *Reophax texanus* Cushman and Waters
(2) *Dorothia bulletta* (Carsey)
(3) *Lenticulina spisso-costata* (Cushman)
(4) *Robulus navarroensis* (Plummer)
(5) *Saracenaria triangularis* (d'Orbigny)
(6) *Marginulina plummerae* (Cushman)
(7) *Dentalina basiplanata* (Cushman)
(8) *Dentalina legumen* Reuss
(9) *Nodosaria affinis* Reuss
(10) *Globulina lacrima* Reuss
(11) *Bolivina* (*Loxostomum*) *gemma* (Cushman)
(12) *Stilostomella alexanderi* var. *impensia* (Cushman)
(13) *Guembelina ultimatumida* White
(14) *Bulimina arkadelphiana* Cushman and Parker
(15) *Epistomina caracolla* (Roemer)
(16) *Cibicidina* cf. *C. subcarinata* (Cushman and Deaderick)
(17) *Anomalina rubiginosa* Cushman

* M. Ruth Todd, United States Geological Survey, personal communication.

The deposits of Pleistocene age above the Gardiners clay are designated upper Pleistocene deposits. They consist of 50 to 100 feet, and in places more, of brown and gray sand and gravel and some thin beds of clay. Near Montauk Point, Suffolk County, they probably include the Montauk till and till of the Ronkonkoma moraine (Fuller, 1914).

The Recent deposits are composed mainly of beach sand and gravel, commonly containing shells and interbedded in a few places with thin layers of clay and silt. Swamp deposits and artificial fill compose the surficial deposits in some parts of the beaches.

Source, Occurrence, and Movement of Ground Water

Ground water beneath the beaches occurs under both unconfined or water-table conditions and confined or artesian conditions. Unconfined water occurs in the shallow Recent and upper Pleistocene deposits. The source of the shallow fresh water is direct precipitation on the beaches. The local water table, or surface of the zone of saturation, is relatively flat, the maximum altitude generally being about 2 to 3 feet above sea level near the center of the beach. The shallow fresh water moves from the water-table divide to discharge areas in the bays and in the Atlantic Ocean.

Artesian water occurs in the Jameco gravel, in several permeable zones in the post-Raritan deposits of Cretaceous age, and in the Lloyd sand member of the Raritan formation. The artesian water is derived generally by underflow from the artesian units inland, which are recharged by downward percolation of water from upper Pleistocene deposits near the middle of the Island. FIGURE 2 shows schematically the general pattern of movement of fresh water in central Suffolk County. The fresh-salt water interfaces shown at the north and south shores are hypothetical, as their actual position and shape are unknown. The geologic units, except the bedrock, are omitted from the illustration for clarity. Extensive clay layers such as the Gardiners clay, thick clays in the post-Raritan deposits, and the clay member of the Raritan formation undoubtedly cause some refraction of the flow lines, but probably do not affect significantly the over-all pattern of movement shown on the illustration. In Kings, Queens, and western Nassau counties the normal pattern of seaward flow is influenced by pumping and by the inland position of the fresh-salt water interface in most of the aquifers. Hence, the movement in those areas may depart considerably from the generalized pattern shown in FIGURE 2.

Geologic Features and Ground-Water Supplies by Areas

Kings County—Seagate to Floyd Bennett Air Field. Section B-B′ (FIGURE 3) shows the thickness and depth of the unconsolidated deposits beneath the beaches of southern Kings County. The deposits range in thickness from about 500 to 800 feet. Two wells, K1 and K1056, were drilled to bedrock and the Lloyd sand member, respectively, and form the principal control for the section. Other wells terminate in Pleistocene deposits. On the basis of data chiefly beyond this section (Suter *et al.*, 1949; deLaguna, 1948) it is thought that the surface of the post-Raritan deposits of Cretaceous age illustrated in FIGURE 3 is considerably more irregular than is shown, and is probably incised by deep channels of streams that formerly flowed toward the south and southwest to an ancient Hudson River. The channels were probably cut in late Tertiary time, and now contain deposits of the Jameco gravel and the overlying Gardiners clay. Logs of several wells suggest that the Gardiners clay is either missing in places, owing to erosion, or is composed mainly of sandy material. Owing to a lack of data, neither the Jameco gravel nor the Gardiners clay is delineated on the Kings County section. Both formations are present in at least part of the area and are included in the unit designated Recent and Pleistocene deposits (undifferentiated).

All the water-bearing units, except perhaps part of the Lloyd sand member, contain salt water. Some water was pumped for industrial use from the Lloyd in the 1930s at well K1. The water contained 4 ppm of chloride and had a temperature of about 60° F. in 1937. The well, which yielded about 1,100 gpm, was abandoned in 1941. Some increases in chloride content of the water were noted during the last two years of operation of the well. It is not known whether the increase in chloride content was the result of salt-water encroachment in the Lloyd sand member or was the result of contamination by salty water leaking down from the post-Raritan Cretaceous deposits through a corroded well casing. The mean daily water level measured at K1057, an observation well screened in the Lloyd sand near K1056, has ranged from about 7 to 11 feet above sea level during the period of record from 1941 to 1958. Daily changes in water level due to the rise and fall of the tide range from about 1 to 1.5 feet. At the present time no water is pumped from the Lloyd sand member in this area.

Most wells drilled on the beaches of Kings County range in depth from about 40 to 260 feet and tap Recent and Pleistocene deposits (Legette *et al.*, 1937; Legette and Brashears, 1944). Most of the shallow wells are screened in the upper Pleistocene deposits, and the deep wells are screened in the Jameco gravel. Individually, they yield 50 to 1,000 gpm. Records of chloride content of the water from a number of these wells show ranges from 170 to 16,000 ppm. Concentrations of other constituents also are high (K318, TABLE 3). The temperature of the ground water ranges from about 50° to 60° F. Most of the water pumped is salty and is used for air-conditioning in theaters and stores, but some is used for salt-water showers at bathhouses and at apartment houses near beaches.

Withdrawals from wells on and near the beaches of southern Kings County average about 0.5 mgd; however, during the air-conditioning season they average about 1.7 mgd, and a substantial part of this water is returned to the ground through recharge wells. The entire area is supplied with water for domestic and other general uses from New York City's upstate reservoirs.

Queens County—Rockaway Point to Far Rockaway. Section *C–C′* (FIGURE 3) illustrates the geologic relations beneath southern Queens County. Bedrock penetrated at a depth of about 975 feet below sea level at one well in Rockaway Park is described as a granite showing no signs of metamorphism (Roberts, 1948). The Raritan formation and the post-Raritan Cretaceous deposits have been penetrated by a number of deep wells. The description of the Cretaceous deposits in well logs and examination of available samples indicate that the deposits are nonmarine. As in Kings County, the surface of the post-Raritan Cretaceous deposits is probably more irregular than is shown on the section. The bottom of one channel cut in Cretaceous deposits is thought to be as deep as 350 feet below sea level. The Jameco gravel occurs beneath the entire area. The depth and continuity of the Gardiners clay are uncertain. In some wells in the central and western parts of the area the surface of the Gardiners clay, if correctly identified, is thought to be as deep as 200 feet below sea level; to the east, the surface of the clay is at an altitude of 100 feet or less below sea level. The Recent and upper Pleistocene deposits have a combined thickness of about 60 to 200 feet.

The Lloyd sand member of the Raritan formation has been and still is the principal source of fresh ground water on the beach. Individual wells have yielded 300 to 2,000 gpm. At Far Rockaway (Q111) the Long Island Lighting Company pumps about 0.4 mgd from two wells in the Lloyd for cooling. This is the only installation in extreme southern Queens County where water is now being pumped from the Lloyd. The water is very soft, but has a high concentration of iron and is acidic (TABLE 3). The static water level is about 9 feet above sea level. The New York City Department of Water Supply, Gas and Electricity formerly operated a group of wells screened in the Lloyd sand at Rockaway Park, but the system is now completely dismantled. Two wells drilled at the Rockaway Park well field in 1939 and 1940 yielded about 2000 gpm each; the water had an initial chloride content of about 40 ppm and a content of about 200 ppm after a short period of operation of the wells. The cause of the increase in chloride content is not known. The water in all the units above the Lloyd sand member, except in part of the Recent deposits, is salty. At Far Rockaway the Long Island Lighting Company pumps about 0.75 mgd of salty water from wells screened in the Jameco gravel at a depth of about 130 feet. Wells at theaters and bathhouses also pump salt water from Pleistocene deposits (Q133, TABLE 3). The wells range in depth from about 100 to 160 feet, and individually yield 50 to 350 gpm (Leggette *et al.*, 1938; Roberts and Jaster, 1947). Some thin lenses of fresh water are present at shallow depths (generally less than 40 feet) in Recent deposits (Q1215, TABLE 3). Fresh water from shallow depths is pumped through well points for use in sprinkling lawns at several places.

Total withdrawals from all aquifers is estimated to be about 1.2 to 1.5 mgd. Most of the water pumped is salty and is used for cooling and air conditioning. Water for domestic and other general uses is supplied from New York City's municipal system.

Nassau County—Atlantic Beach to Nassau-Suffolk County Line. In section D-E (FIGURE 4), the unconsolidated deposits range in depth from about 1150 feet below sea level at the west end to 1700 feet below at the east end. A deep well at Long Beach (not shown on the section) penetrated granite gneiss at about 1460 feet below sea level. According to present knowledge, the Cretaceous deposits are entirely nonmarine. Lignite, spores, and pollen are abundant, especially in the post-Raritan Cretaceous deposits. The upper surface of the Cretaceous beds ranges in depth from about 80 to 200 feet below sea level, and erosional channels are more prominent in the western part of the area. The Jameco gravel occurs in the area from about Lido Beach west to the county line and is continuous with the same deposits in Queens County. The Gardiners clay overlies the Jameco gravel in the western part in the Cretaceous deposits in the eastern part. The Recent and upper Pleistocene deposits are composed chiefly of sand and gravel and have a combined thickness of 50 to 100 feet.

Fresh water is present in the Lloyd sand member throughout the area and in the post-Raritan Cretaceous deposits in the eastern half of the area. The Lloyd sand member is the chief source of fresh water and is reserved exclusively for public supply. Wells ranging in depth from about 1000 to 1300 feet and yielding 700 to 1400 gpm are operated by public-supply systems at Atlantic Beach, Lido Beach, and Long Beach. The static water levels range from about 10 to 15 feet above sea level, and some wells flow. The water in the Lloyd has less than 10 ppm of chloride and low concentrations of other constituents, except for iron, which is present in concentrations as high as 8 ppm (N4405, TABLE 3). In 1957 an average of about 5.2 mgd was pumped from the Lloyd sand member, the peak pumpage being as much as 10 mgd during the

TABLE 3

CHEMICAL ANALYSIS OF WATER FROM SELECTED WELLS ON SOUTH-SHORE BEACHES, LONG ISLAND, N. Y.

(Chemical constituents in parts per million. Numbers rounded off in accordance with geological survey practice)

Well number	Location	Depth below land surface (feet)	Water-yielding unit	Date of collection	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na + K)	Bicarbonate (HCO$_3$)	Sulfate (SO$_4$)	Chloride (Cl)	Nitrate (NO$_3$)	Dissolved solids	Hardness as CaCO$_3$	Alkalinity as CaCO$_3$	*p*H
K318	Coney Island, Kings County	135	Pleistocene deposits	Aug. 4, 1942	0.3	—	—	—	—	—	14,750	0	—	5,750	144	—
K1243	Coney Island, Kings County	40	Recent(?) deposits	Aug. 7, 1942	.1	—	—	—	—	—	183	9.8	—	330	156	—
Q111	Far Rockaway, Queens County	1,003	Lloyd sand member of Raritan formation	July 25, 1950	6	—	—	—	—	17	20	—	77	14	9	5.6
Q133	Rockaway Park, Queens County	99	Upper Pleistocene deposits	Sept. 23, 1942	6	—	—	—	—	—	6,350	0	—	900	166	—
Q1215	Hammels, Queens County	35	Recent(?) deposits	July 29, 1942	.8	—	—	—	—	—	40	1.5	—	180	122	—
N127	Short Beach Coast Guard Station, Nassau County	303	Post-Raritan Cretaceous deposits	May 2, 1933	2.0	1.0	—	—	10	20	7	0	—	4	—	—
N129	Jones Beach, Nassau County	951	Post-Raritan Cretaceous deposits	Nov. 10, 1953	.2	.5	0.2	31	37	29	4.7	.3	96	2	—	6.2
N3498	Tobay Beach, Nassau County	335	Post-Raritan Cretaceous deposits	Nov. 13, 1958	3.2	—	—	—	—	—	10	.4	—	8	16	6.2
N4405	Atlantic Beach, Nassau County	1,075	Lloyd sand member of Raritan formation	Sept. 15, 1954	7.9	2.0	.7	13	6.4	15	10	.1	53	8	—	6.8
S40	Ocean Beach, Suffolk County	420	Post-Raritan Cretaceous deposits	Oct. 7, 1958	.03	—	—	—	—	—	4.8	.15	—	4	15	6.6
S3839	Bellport Coast Guard Station, Suffolk County (near S15,006T)	377	Post-Raritan Cretaceous deposits	Sept. 7, 1956	4.1	1.2	1.4	9.2	18	4.9	4.5	—	40	10	—	6.8
S5997	Hither Hills State Park, Suffolk County	120	Upper Pleistocene deposits	July 31, 1947	.1	—	—	—	—	—	57	—	—	50	42	—

summer months. Most of the water was pumped by the city of Long Beach. Several wells ranging in depth from about 500 to 1000 feet have been drilled in the post-Raritan Cretaceous deposits in the area from Lido Beach to Jones Beach. The water levels increase from about 4 feet above sea level in the western part to 9 feet above in the eastern part of the area. Individual wells yield 200 to 1200 gpm. Pumpage averaged about 0.26 mgd in 1957, and was mostly from three wells each about 1000 feet deep at Jones Beach State Park. The fresh water in the upper and lower parts of the post-Raritan Cretaceous deposits has a chloride concentration and hardness of less than 10 ppm (N127, N129, N3498, TABLE 3).

FIGURE 4 shows that salt water is present in the form of an upper and a lower wedge in the post-Raritan Cretaceous and Pleistocene deposits in the western part of the area. The lower wedge is part of a larger body which extends west and north into Queens County. The Pleistocene and Recent deposits contain chiefly salty water. A few air-conditioning wells draw water from these deposits, and a small number of shallow well points probably tap relatively thin fresh-water zones in the Recent deposits. Records of wells in Nassau County are given in reports by Leggette *et al.*, 1938; Roberts and Brashears, 1946; and Johnson *et al.*, 1958.

Western Suffolk County—Nassau-Suffolk County Line to Hampton Beach. Section *E–F* (FIGURE 5) shows the geologic relations beneath the beaches of western Suffolk County, where the unconsolidated deposits range in depth from about 1700 to 1900 feet. One well S15,106T (Bellport Coast Guard Station) penetrated granitic bedrock at about 1900 feet. The Raritan formation extends beneath the entire area, but the subdivision of the formation into a clay member and a sand member is based largely on extrapolation of data to the west and north. The depth to the top of the Raritan formation shown at well S15,106T is considered tentative, as no thick distinctive clay member was noted in the driller's, electric, neutron, and gamma-ray logs. It is entirely conceivable that the Raritan formation there consists of alternating beds of clay and of sand and gravel. The post-Raritan deposits of Cretaceous age are similar lithologically to those found farther west, except that in this area a fossiliferous glauconitic clay and sandy clay (designated the greensand unit) occurs in the upper part between depths of about 100 to 300 feet below sea level. The greensand unit is immediately overlain by the Gardiners clay. The Jameco gravel is missing in this section. The Recent and upper Pleistocene deposits consist chiefly of beds of coarse sand and gravel generally having a total thickness of about 100 feet.

Available well data and the electric log for the deep well S15,106T suggest that the Lloyd sand member and the post-Raritan deposits of Cretaceous age, with the possible exception of the greensand unit, contain fresh water. Supply wells for a number of State parks, beach communities, and Coast Guard stations on Fire Island Beach pump water from the post-Raritan Cretaceous deposits at depths ranging from about 300 to 500 feet below sea level (Leggette *et al.*, 1938; Roberts and Brashears, 1945; and Johnson *et al.*, 1952). Individual wells yield about 30 to 550 gpm and have specific capacities ranging from about 2 to 25 gpm per foot of drawdown. Many of the wells flow, some at rates as much as 50 gpm. Altitudes of water levels range from about 8 to 20 feet above sea level, and are highest at the bottom of the deposits. The water is very soft and generally has a chloride concentration of less than 5 ppm (S40 and S3839, TABLE 3). The temperature of the water increases with depth, and ranges from about 55° to 60° F. Total withdrawals from the post-Raritan Cretaceous deposits during 1957 averaged about 0.23 mgd, but during the summer months, when most of the water was pumped, the withdrawals averaged about 0.7 mgd. No water is pumped from the Lloyd sand member in southwestern Suffolk County.

Salt water having a chloride content of as much as 17,500 ppm is present in most of the upper Pleistocene and Recent deposits above the Gardiners clay. Lenses of fresh water as much as 40 feet thick are present in Recent deposits where the water table rises 1 to 2 feet above sea level near the center of the beaches. This fresh water commonly is used to supply summer bungalows.

Eastern Suffolk County—Hampton Beach to Montauk Point. Section *F–G* (FIGURE 6) shows the extent of present knowledge of the geologic units beneath the south-shore beaches of eastern Suffolk County. The delineation of the upper surfaces of the bedrock and the Raritan formation are based mainly on extrapolation of a few data from deep wells to the west and north. Some additional control for the bedrock surface was adapted from a seismic survey of the basement rocks offshore (Oliver and Drake, 1951). The thickness of the unconsolidated deposits is estimated to range from about 1850 feet at the west end to 1100 feet at the east end. The subdivision of the Raritan formation into two members is entirely hypothetical, as no deep wells have penetrated the formation in this area. The greensand unit at the top of the post-Raritan deposits is thought to be present at the west end of the section, and may extend as far east as well S1399 (Napeague Beach). The Gardiners clay overlies Cretaceous deposits in most of the area, but near Montauk Point it probably overlies the Jameco gravel. The Pleistocene deposits at the extreme east end of the section are undifferentiated and may include the Jameco gravel, Gardiners clay, Montauk till and till of the Ronkonkoma moraine (Fuller, 1914), and outwash of Wisconsin age.

Drillers' records of several wells that penetrate salt water, the small area of recharge to the north, and the low altitude of the main water table on the South Fork are the basis for showing (FIGURE 6) that practically all the deposits are saturated with salt water. The position of the fresh-salt water interface at the west end of the section is conjectured. Fresh water is present in thin lenses in the Recent and Pleistocene deposits in several places in the area extending about five miles west from Montauk Point. The analysis of water from well S5997, which taps relatively fresh water at Hither Hills State Park, about five miles west of Montauk Point, is given in TABLE 3.

Pumpage from wells directly on the beaches probably is less than 0.1 mgd. Public-supply wells, owned by the Suffolk County Water Authority, and several private water companies are roughly within ½ mile to 2 miles inland from the shore line, and yielded a total of about 2.1 mgd in 1957. The water was pumped from wells in upper Pleistocene deposits ranging in depth from about 40 to 100 feet. Some of the water from inland wells was distributed through mains to beach communities that have no source of fresh ground water.

Availability of Additional Supplies of Fresh Water

Development of additional supplies of fresh water from wells on beaches is in part contingent on knowledge of the occurrence of nearby salt-water bodies and their rate of movement, if any, toward wells. The sections in FIGURES 3, 4, 5, and 6 summarize present knowledge of the occurrence of fresh- and salt-water bodies. The data are by no means precise, and much can be learned from additional test holes and wells that are cored at short intervals and are electrically logged. The rate of movement of salt water depends in part on the relation of hydraulic gradients in the fresh and salt water and, in part, on the porosity and permeability of the aquifers. For most existing well installations on the beaches, it is virtually impossible from present knowledge to compute rates of movement of salty water and thus predict when an installation may be contaminated by salt water. Furthermore, the aquifers beneath the beaches are particularly vulnerable, as they can be contaminated by sea water drawn in as a result of heavy pumping from inland wells that lowers fresh and salt water heads at the shoreline.

In Kings County, probably the only source of fresh water in appreciable amounts is the Lloyd sand member of the Raritan formation. However, even this aquifer cannot be heavily pumped without causing sea-water encroachment, as the fresh-salt water interface in the Lloyd is thought to lie at and close to the shore line. The overlying aquifers contain only salt water. Probably much of the salt water in these aquifers was induced to flow in by many years of heavy pumping of wells to the north in the vicinity of Flatbush in the central part of the county. Recovery of water levels to altitudes above sea level is proceeding in central Kings County, owing to shutdown of heavy pumping in 1947 (Lusczynski, 1952), but it is doubtful that the aquifers beneath the beaches will be completely flushed of salt water for many years.

The situation in southern Queens County is similar to that described for Kings County. All the aquifers except the Lloyd sand member contain salty water. As long as about 45 to 50 mgd is pumped from wells in a relatively small area in central Queens, it is doubtful that significant quantities of fresh water can reach Rockaway Beach to flush salt water out of the artesian aquifers. Large-scale development of the Lloyd sand member by means of wells on the beach is likely to cause encroachment in that aquifer, as the fresh-salt water interface is probably close to shore. Also, under present conditions, most of the recharge to the Lloyd in southern Queens seems to come from Nassau County, where the Lloyd is rather heavily pumped by means of wells on the beaches.

In Nassau County most of the fresh water pumped by wells on the beaches comes from the Lloyd sand member. Interference between pumped wells is common. The fresh-salt water interface in the Lloyd lies offshore, but the distance is unknown. East of Lido Beach both the Lloyd sand member and the post-Raritan Cretaceous deposits contain fresh water, and seem capable of yielding additional supplies. The fresh-salt water interface in both these aquifers lies farther seaward than in the area to the west; however, fresh-water levels are below the minimum considered necessary to keep out salt water. Beneath Atlantic Beach and part of Long Beach the salt water in the post-Raritan deposits is moving landward at a slow rate (Perlmutter *et al.*, 1957).

It is not considered feasible to develop large supplies of fresh water in the post-Raritan deposits near this body of salty water.

The beaches of western Suffolk County are most favorably situated with respect to potentiality for development of additional supplies of fresh water. Nearly the entire thickness of Cretaceous deposits below the greensand unit contains abundant quantities of fresh water that are virtually untapped. Furthermore, the water table in the recharge area to the north has not been lowered during the past 50 years, as withdrawals in western Suffolk County account for only a small part of the available recharge. It is reasonable to suppose that the artesian aquifers beneath the barrier beaches of western Suffolk County are capable of yielding at least the amount of fresh water pumped in the smaller but hydrologically similar area of southern Nassau County: that is, at least 5 mgd.

The aquifers of eastern Suffolk County are almost completely saturated with salty water. Hydrologic conditions are not favorable for seaward discharge of large amounts of fresh water in the deeper aquifers, and only scattered small supplies of fresh water can be developed from shallow wells. When the shallow wells are pumped too heavily, the chloride content of the water soon rises as salt water moves toward the wells from the underlying deposits and laterally from the bays and the ocean. A potential source of additional large supplies of fresh water in eastern Suffolk County and elsewhere would be the development of an economical salt-water conversion unit that could utilize the large quantities of brackish ground water that can be pumped from wells

Summary

In 1957 an average of 7 million gallons per day (mgd) of water was pumped from wells screened in Upper Cretaceous, Pleistocene, and Recent deposits beneath the south-shore beaches of Long Island. These deposits have a total thickness of about 500 to 1900 feet. The Upper Cretaceous deposits consist of the Lloyd sand member of the Raritan formation, confined by the clay member of that formation, and of younger beds that include the Magothy formation. In part of Suffolk County the uppermost Cretaceous unit is a fossiliferous green sand tentatively correlated with the Navarro group of Texas. The Cretaceous aquifers contain fresh water in much of the area, but yield salty water in the extreme eastern and western parts. Two Pleistocene aquifers, separated by an interglacial clay, contain fresh water in some places and salty water in others. Recent deposits commonly contain salty water except for a thin lens of fresh water floating on salt water in the uppermost part.

The Recent and upper Pleistocene deposits are recharged by local precipitation. The deeper Pleistocene and Cretaceous artesian aquifers are recharged mainly by underflow from the middle of the island. The problem of sea-water encroachment should be considered in planning additional large developments.

Acknowledgments

We acknowledge the cooperation of the Long Island State Park Commission, the Suffolk County Health Department, and the Department of Water Supply, Gas, and Electricity of the City of New York for providing data on

the chemical quality of water. We are grateful in particular to the New York State Water Power and Control Commission, for records of wells and data on pumpage.

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GROUND-WATER SUPPLIES IN PLEISTOCENE AND CRETACEOUS DEPOSITS OF NORTHWESTERN NASSAU COUNTY, N. Y.*

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Introduction

In cooperation with the Nassau County Department of Public Works and the New York State Water Power and Control Commission, the United States Geological Survey has completed the field work of a rather detailed areal investigation of the geology and occurrence of ground water in northwestern Nassau County, N. Y. This paper is based on field observations made since 1955, including mapping of the surficial deposits of the area, collection of subsurface geologic data, correlation of rock samples with stratigraphic units known to occur elsewhere on Long Island, and data gathered in a program of systematic water-level measurements. In the course of the investigation two observation wells were drilled to bedrock, in Great Neck and Sands Point, respectively. The Geological Survey also installed 16 shallow water-table observation wells. Existing information, published and unpublished, was used freely in the present effort toward solving the complex geologic and hydrologic problems of the project area. The work of earlier investigators is acknowledged thankfully.

The area of investigation (FIGURES 1 and 4) comprises about 63 square miles, 52 square miles of which is in Nassau County and the remainder in northeastern Queens County. In Nassau County, the area includes nearly all villages within the town of North Hempstead west of Westbury, plus the Glen Cove and Sea Cliff sections of the town of Oyster Bay. It extends southward to Garden City.

Physiography

The area may be subdivided into three morphologic units, from north to south (1) the headlands, including Great Neck and Manhasset Neck; (2) the Harbor Hill terminal moraine; and (3) the glacial outwash plain. The headlands rise abruptly from Long Island Sound and its bays to rather uniform elevations of 80 to 100 feet at their northern tips. Southward the headlands, which are mantled thinly by glacial till, become increasingly irregular and rise to elevations above 200 feet. The Harbor Hill terminal moraine, consisting of a series of coalescing irregular hills, forms a pronounced ridge trending to the northeast, rising 80 to 150 feet above the headlands. The highest elevations found in western Long Island occur along this ridge, Harbor Hill itself rising to 368 feet above sea level. The glacial outwash plain of sand and gravel abuts the moraine, sloping southward from an altitude of about 140 feet at the south edge of the moraine to about 80 feet in Garden City; thence its gentle southward slope is continued to the shore areas of southern Nassau County.

There are no large streams in the area. Existing small streams, sustained

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* Prepared in cooperation with the Nassau County Department of Public Works, Mineola, N. Y., and the New York State Water Power and Control Commission, Albany, N. Y., and authorized for publication by the United States Geological Survey, Washington, D. C.

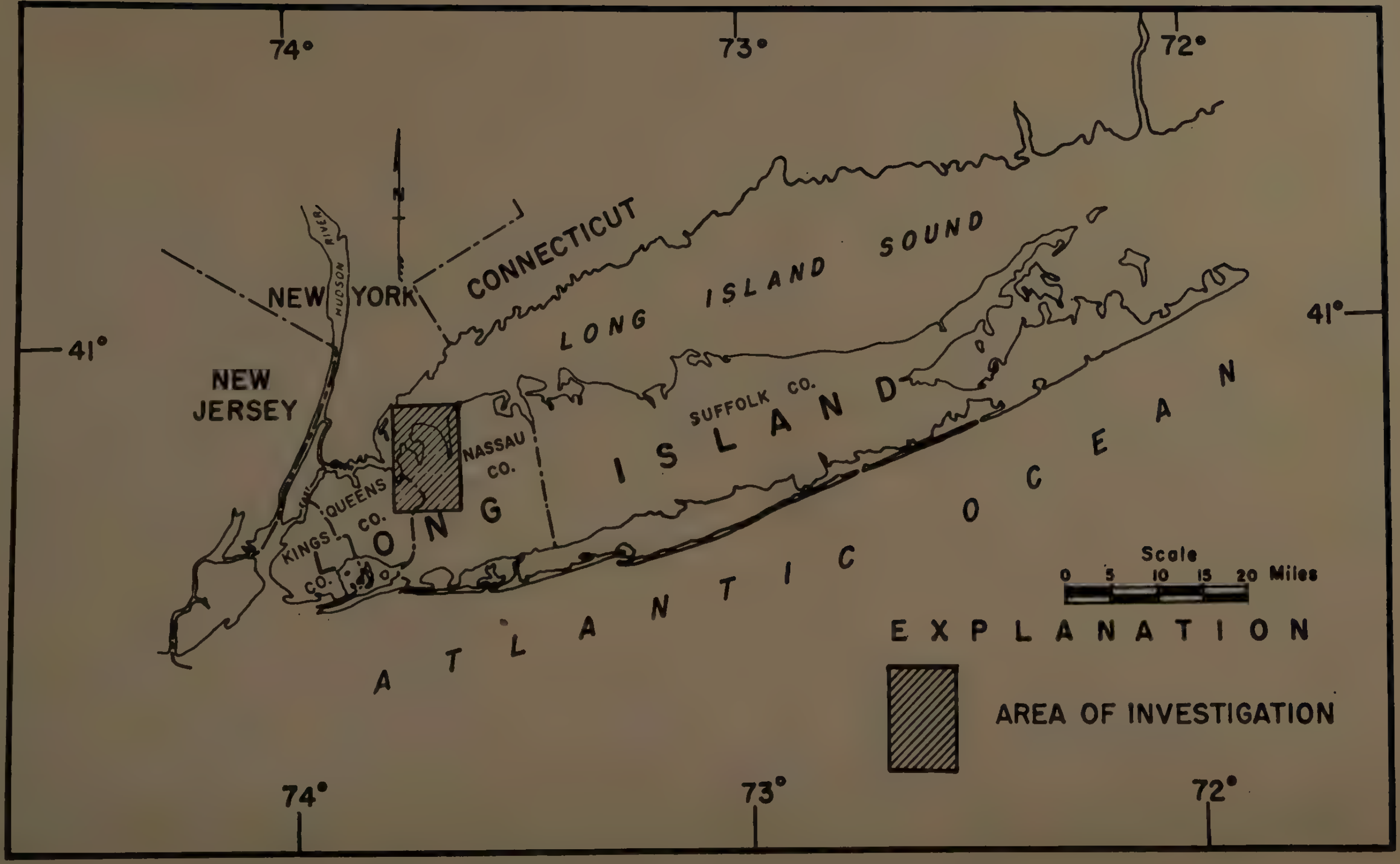

FIGURE 1. Map of Long Island, N. Y., showing area of investigation.

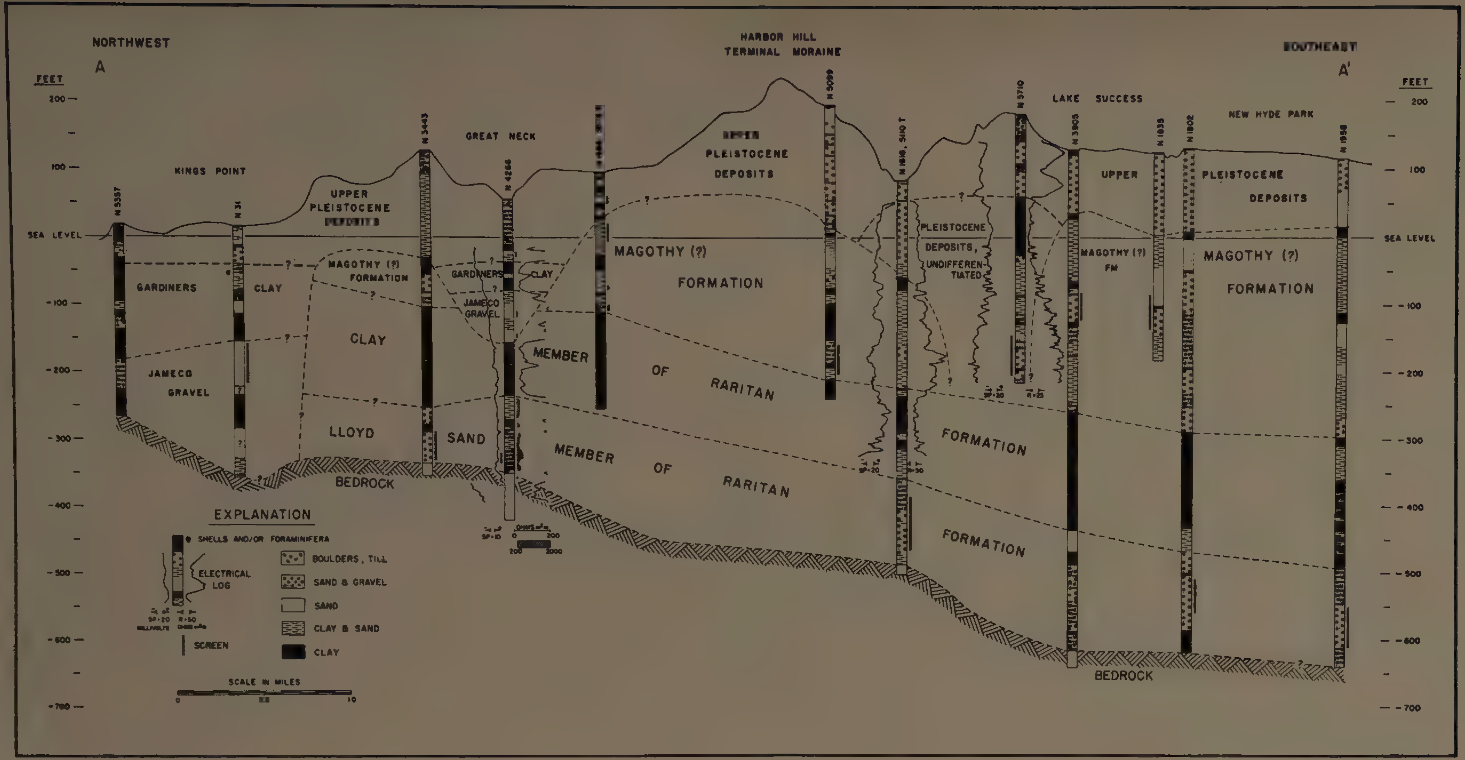

FIGURE 2. Geologic section A-A′ from Kings Point to New Hyde Park, N. Y.

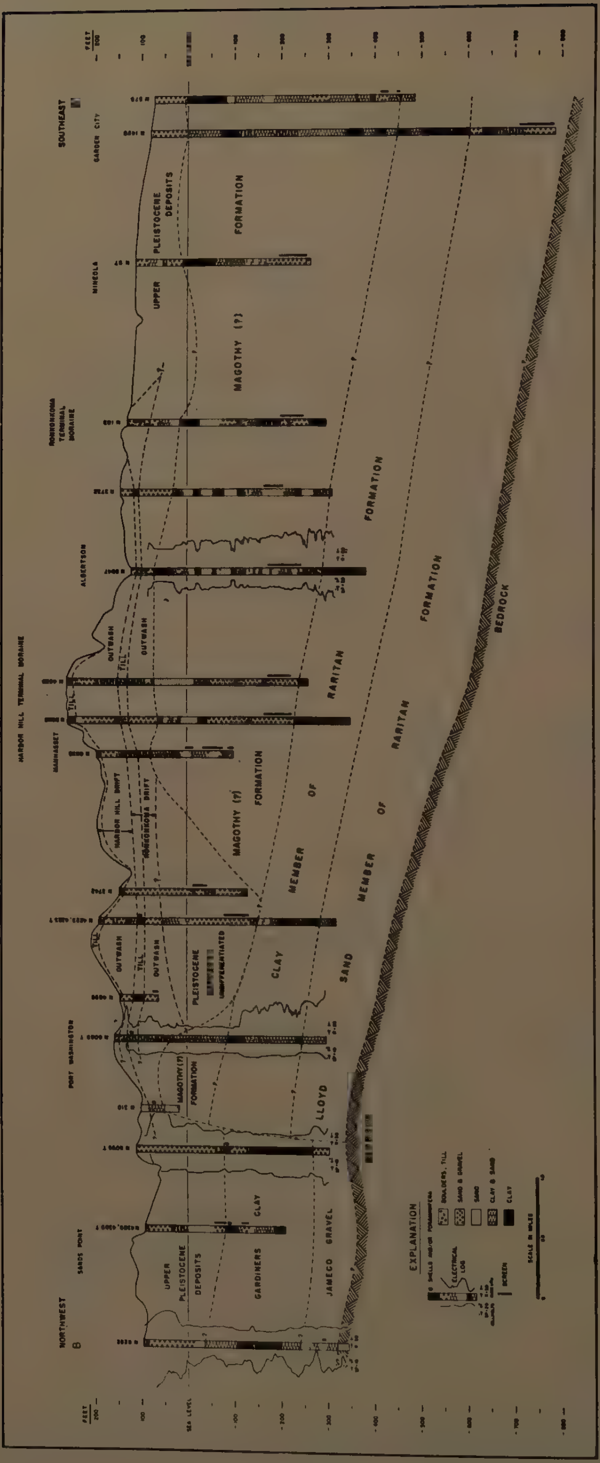

FIGURE 3. Geologic section B-B′ from Sands Point to Garden City, N. Y.

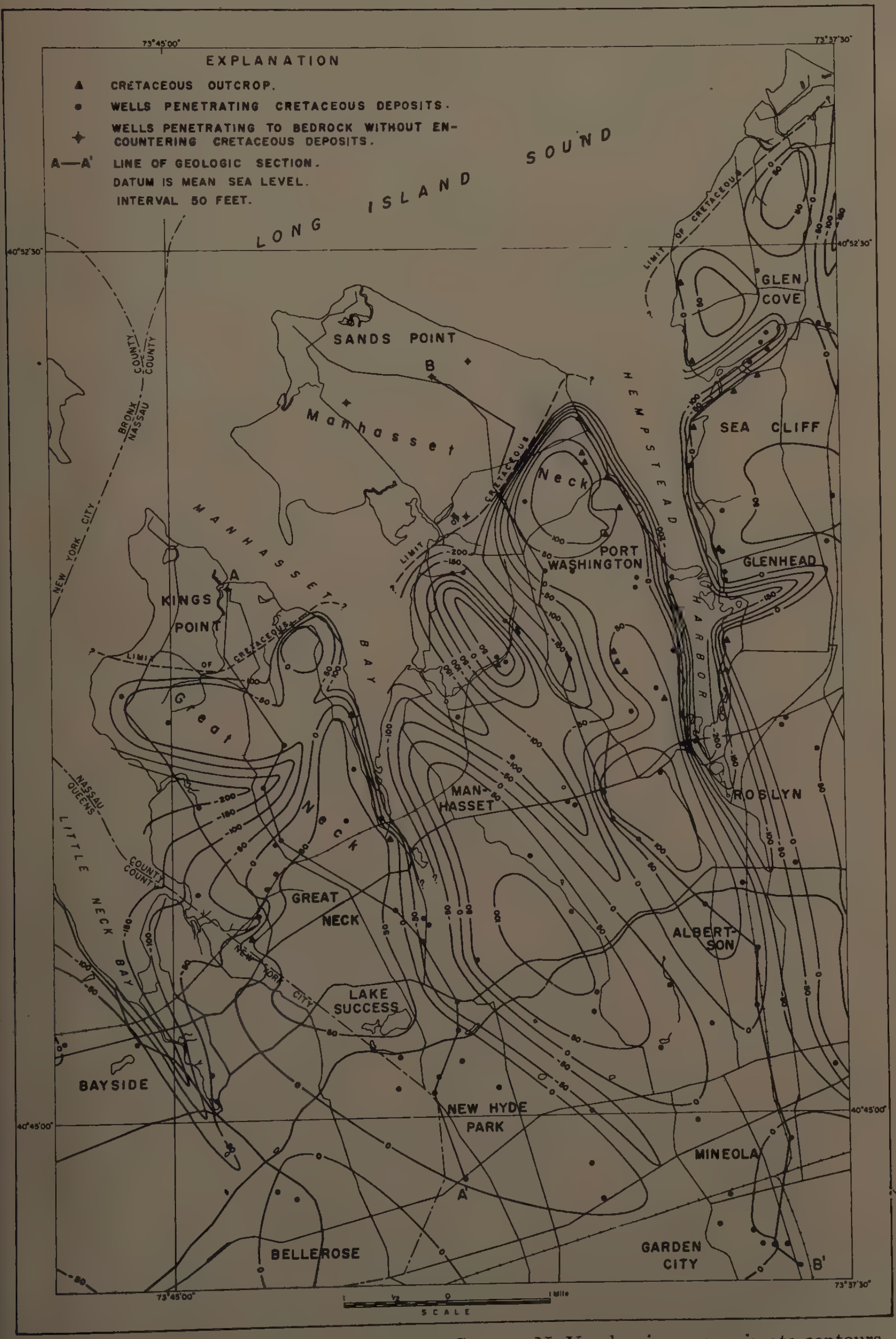

FIGURE 4. Map of northwestern Nassau County, N. Y., showing approximate contours on the buried Cretaceous surface.

by local ground-water outflow, flow predominantly to the north and west at average rates of 0.25 to 3.0 cubic feet per second (cfs). Nearly all are small in relation to the valleys they occupy. The oversized valleys originated in Pleistocene time, except for those forming the north-shore harbors, which are of pre-Pleistocene origin.

Geology

The subsurface strata of Long Island consist of unconsolidated Pleistocene and Cretaceous sediments that rest on a crystalline bedrock surface sloping to the southeast. The bedrock is though to be of Precambrian or early Paleozoic age.

In the area of investigation the bedrock is generally a biotite schist or gneiss, in most places strongly weathered in its upper part. Some test wells penetrated more than 70 feet of weathered bedrock without reaching fresh rock. Bedrock occurs at depths ranging from about 200 to 800 feet below sea level, forming a basement that slopes to the southeast at approximately 50 feet per mile. However, there are indications that this regional slope is locally reversed in the northern part of Manhasset and Great Neck. For example, well data seem to indicate a leveling off or reversal of bedrock slope in Sands Point, Port Washington, and Kings Point (see FIGURES 2 and 3). Channel cutting to a depth slightly greater than 350 feet below present sea level seems to have occurred during a pre-Wisconsin stage of the Pleistocene when sea level was perhaps 400 feet lower than at present. Erosion at that time appears to have removed the bulk of Cretaceous deposits in the northernmost areas of Kings Point and Manhasset Neck. Undoubtedly, there are other variations in the relief of the bedrock surface which can be revealed only by exploratory drilling.

The Cretaceous deposits of Long Island, lying unconformably above bedrock, consist of interbedded sand, gravel, silt, and clay that are dominantly of terrestrial origin. Two formations are recognized: the older Raritan formation, which is divided into the Lloyd sand member below and the clay member above, and the Magothy(?) formation. The Raritan formation, by correlation with New Jersey formations, has been referred to the basal part of the Upper Cretaceous series. The term Magothy(?) formation, used to designate all Cretaceous strata on Long Island that lie above the Raritan formation, probably includes an equivalent of the Magothy formation of New Jersey and also some Upper Cretaceous strata younger than the Magothy of New Jersey.

The Cretaceous deposits, known almost entirely from well logs, attain their greatest thickness in the project area in the vicinity of Garden City. Here the Cretaceous begins about at sea level and extends to about 800 feet below; it is divided about equally between the Magothy(?) and Raritan formations. The Lloyd sand member of the Raritan formation, lying on bedrock, has an average thickness of 200 to 250 feet; it is a relatively permeable artesian aquifer, composed of white or gray sand and gravel which, in many places, has a clayey matrix. Lenses of clay and clayey sand are common. The clay member of the Raritan formation, lying above and confining the Lloyd sand member, consists of about 100 to 200 feet of solid and silty clay, usually dark gray, with lignitic zones. Colors are variable and include red, white, and variegated. Gravelly strata and calcareous concretionary zones also have been reported. The top of the clay member of the Raritan formation occurs at about 100 feet below sea level in Great Neck and Port Washington, and the formation slopes to the southeast at a rate similar to or slightly less than that of the underlying bedrock. The Magothy(?) formation within the project area is slightly more than 400 feet thick at the maximum, and consists chiefly of fine sand, sandy clay, and clay. Gravel occurs in a zone near the bottom and in lenses at somewhat higher elevations, and it yields by far the largest share of the water pumped in the area. The Magothy(?) formation is characteristically lenticular, although locally it may consist almost entirely of fine clayey sand and silt. The colors are usually gray, white, pink, or red; lignite, pyrite, and iron oxide concretions are common throughout.

FIGURE 4 is a contour map showing approximately the extent and relief of the eroded and buried Cretaceous surface. Cretaceous deposits occur in almost the entire project area, except in the northern tips of Manhasset and Great Necks. In Kings Point and Sands Point the northern limit of the Cretaceous is marked by a buried cuesta apparently formed in clay of the Raritan formation at and below sea level. Quite possibly this cuesta originated as the obsequent north-facing slope of a strike valley cut to or nearly to bedrock in post-Cretaceous time. Later, erosion during the Pleistocene is thought to have removed all Cretaceous sediments in the northern parts of the peninsulas, leaving isolated remnants to the east and west and probably in the wider parts of Long Island Sound.

The relief of the Cretaceous surface, moderate in the southern part of the area but more pronounced in the north, was created by post-Cretaceous consequent streams draining toward the Atlantic Ocean. Obsequent streams flowing into the strike valley now forming Long Island Sound were responsible for more than 400 feet of relief in the Cretaceous surface along the north shore. The irregularities of the Cretaceous surface are only locally and fortuitously revealed by well-drilling data.

Pleistocene deposits locally comprise all or most of the unconsolidated sediments above bedrock and assume special importance wherever they are part of the ground-water reservoir. Everywhere the Pleistocene sand, gravel, and till form the surficial deposits and, because of their varying permeability, determine the rate at which precipitation infiltrates to the main ground-water body. A special effort was therefore made to recognize the various glacial and interglacial deposits and their age relationships as revealed both at the surface and in wells. From my own observations, and in accordance with the opinions expressed by other writers (Fleming, 1935; MacClintock and Richards, 1936), I favor a simpler sequence of Pleistocene events than that offered by Fuller (1914). Accordingly, the Pleistocene deposits are referred to two glacial stages, separated by an interglacial marine deposit, the Gardiners clay.

The oldest glacial deposit, believed to represent the Jameco gravel, consists of sand, gravel, and silt lying on bedrock or in valleys cut into the Cretaceous sediments. The deposit apparently represents glacial outwash from an ice sheet that did not reach Long Island. It is recognized only in areas where it is overlain by the Gardiners clay, and apparently is of pre-Sangamon, perhaps Illinoian, age. In contrast to the heterogeneous composition of the formation in the type locality in Queens, the Jameco gravel in the project area seems to be largely derived from Cretaceous sources and contains only a small admixture of erratic material. The Jameco occurs generally from 150 to 350 feet below sea level in near-shore areas. Undifferentiated Pleistocene valley fill, occurring at somewhat higher elevations inland (see FIGURES 2 and 3), may be in part equivalent to the Jameco gravel. However, in most cases this valley fill cannot be positively identified because of lithologic similarity to the overlying younger outwash.

A marine formation occurring close to the north shore, in present embayments and former channels, has been recognized in many wells in Great and Manhasset Necks. The formation is thought to be the Gardiners clay, named for Gardiners Island at the east end of Long Island. It consists of greenish-brown clay and silt and scattered occasional sand and gravel lenses. Plant debris ranging from fairly fresh to lignitic is found in some zones. The top of the formation lies usually between 50 and 60 feet below sea level; the thickness is variable, but ranges commonly from about 150 to 200 feet. The formation is in part fossiliferous, containing fragments of oyster and clam shells and, commonly, Foraminifera. Of the latter, *Elphidium* seems to be the most common genus. A fossiliferous zone of some continuity occurs in the northern part of Manhasset Neck between 80 and 100 feet below sea level (test borings N4389T and N6095T, shown in FIGURE 3). No systematic study of the fossil material was possible during the present investigation. Such fossils as were noted are equally characteristic of Pleistocene and Recent marine deposits. Only a detailed ecological study of the microfauna might give some clues as to the depositional environment of the Gardiners clay of the north shore, including salinity, depth, and temperature ranges. In lithology the Gardiners clay of northwestern Nassau County resembles closely the formation in other parts of Long Island, and may in part represent deposition in shallow, brackish water (Weiss, 1954). Nearshore deposition is indicated by the common presence of vegetable debris and gravelly zones within the clay.

The Gardiners clay might have been deposited at a time when sea level was about 50 feet lower than at present. Its age and general correlation with the Gardiners clay of Cape Cod are dubious. The formation is usually regarded as being of interglacial, pre-Wisconsin origin, although an early Wisconsin interstadial age is not impossible (Flint, 1957). C^{14} dates obtained for oyster shells from two localities thought to represent the Gardiners clay indicated an age greater than 38,000 years (Meyer Rubin, United States Geological Survey, personal communication, 1957).

In spite of uncertainties as to its age and origin, the Gardiners clay is a valuable key horizon in Pleistocene stratigraphy for the area. The formation is apparently present in Great Neck, Kings Point, and Sands Point, and is believed to exist also in the north-shore bays and Long Island Sound, dissected by subsequent Pleistocene and Recent erosion. Although the formation is variable enough in thickness and lithology to permit local interchange of water with adjacent formations, it generally constitutes a confining bed creating artesian conditions in the underlying Jameco gravel.

The thrusting action of later Pleistocene ice advances deformed the Gardiners clay in some places, raising it above sea level. Large masses of the formation were found to be incorporated in the lower of two till sheets in Port Washington, at elevations ranging from a few feet below to 150 feet above sea level.

The term "upper Pleistocene deposits" was introduced by deLaguna (1948) for all glacial deposits occurring above the Gardiners clay on Long Island. In large part these deposits appear to be related to two ice advances, and they are subdivided in the project area into the Ronkonkoma and Harbor Hill drifts. The older of these two drifts, the Ronkonkoma drift, includes a terminal moraine of the same name and related outwash deposits and till. The Ronkonkoma terminal moraine is relatively indistinct in western Nassau County, where it is largely mantled by younger outwash. However, it can be traced westward from Albertson to Lake Success, where it merges with the Harbor Hill terminal moraine. A sheet of till, apparently fairly continuous and recognizable in many wells, has been traced beneath younger drift southward from Manhasset Neck to the position of the Ronkonkoma terminal moraine (see geologic section B-B′, FIGURE 3). This sheet is generally 10 to 20 feet thick and consists of compact clayey or sandy boulder till. The top of the till occurs generally at elevations slightly above 100 feet, but may be as high as 150 to 170 feet above sea level. The till, extending southward from Manhasset Neck to Albertson, is correlated here with the older till exposed in several gravel pits on the west shore of Hempstead Harbor at elevations of about 100 feet above sea level. The till and the underlying outwash gravel, respectively the Montauk till member and the Herod gravel member of the Manhasset formation described by Fuller, are interpreted as the ground moraine and advance outwash deposits of the Ronkonkoma ice invasion.

The younger Harbor Hill drift consists of outwash deposits, a veneer of ground moraine and a terminal moraine. Stratified sand and gravel deposits occurring above the Ronkonkoma drift or, as in Great Neck, directly upon the Cretaceous apparently represent advance outwash from the Harbor Hill ice. These deposits, generally 20 to 50 and in places up to 80 feet thick, probably include the Hempstead gravel member of the Manhasset formation. To the north of the Harbor Hill terminal moraine these outwash deposits are covered by a veneer of ground moraine, usually a clayey or sandy till containing boulders; it is generally 5 to 10 feet but locally up to 40 feet thick, and in places is very compact. The Harbor Hill terminal moraine, a distinct northeast-trending ridge, consists largely of ice-contact deposits which, in their alignment, indicate the position of an ice front which was stable for a considerable time. Isolated or coalescing kames and interspersed kettle holes account for the irregular surface of the moraine. Characteristic are steeply inclined, crudely stratified sand and gravel deposits showing slump and collapse features. Till is generally present, but highly irregular in distribution and thickness. Sloping southward from the terminal moraine is a glacial outwash plain of stratified sand and gravel. The surface of this plain is somewhat irregular and pitted by kettle holes as far south as the Ronkonkoma terminal moraine, but still farther south the surface becomes relatively smooth.

There is no evidence that would justify the subdivision of Long Island's upper Pleistocene deposits into units representing more than one glacial stage. All deposits above the Gardiners clay seem to be closely related to the two ice advances which produced the Ronkonkoma and Harbor Hill terminal moraines. There are no indications of a significant erosional interval or fossil soil development anywhere in the upper Pleistocene sequence; there are no obvious lithologic differences between the oldest and youngest outwash deposits; and there is no difference in the degree of weathering of rock pebbles in till or outwash other than that which can be attributed to variations in mineral composition and texture. Thus, apparently no great time elapsed between the Ronkonkoma and Harbor Hill ice advances, which therefore might be considered episodic within one glacial substage. MacClintock and Richards (1936, p. 336) and Flint (1957, p. 356) consider the Pleistocene deposits of Long Island above the Gardiners clay to be of Wisconsin age.

Hydrology

The unconsolidated deposits of Cretaceous to Pleistocene age described in the preceding pages form the ground-water reservoir of the area to the extent of their saturation with water. The sediments are saturated from the weathered bedrock upward to the water table, which represents the upper limit of the zone of saturation. The water table (FIGURE 5) rises from sea level to locally more than 100 feet above sea level. The elevation and slope of the water table are determined by the thickness and permeability of the saturated materials and the rate at which water moves through them: that is, the water table expresses a dynamic equilibrium among all factors affecting ground-water recharge and discharge, both natural and artificial. Variations in any one of the factors may produce changes in the position of the water table and concomitant changes in storage. The ground-water reservoir on Long Island is replenished solely by precipitation, which in Nassau County averages about 43 inches annually. Of this, perhaps 50 per cent percolates to the water table at an average recharge rate equivalent to about 1 million gallons per day (mgd) per square mile. This rate of recharge is probably high for the northern part of the project area, where till and Cretaceous clay near the land surface impede infiltration and increase surficial runoff, and locally perch water in surficial sands. Even under optimum conditions, however, recharge to the water table is chiefly dependent upon precipitation during the winter months. The water of summer rains is to a large extent intercepted by growing plants, and little or no ground-water replenishment may occur during that time. Normally, precipitation in Nassau County is fairly evenly distributed throughout the year.

Withdrawals are made from the more permeable zones of three discrete water-bearing units within the ground-water reservoir: the shallow unconfined aquifer, the principal aquifer, and the deep confined aquifer. The relatively impermeable clay member of the Raritan formation and the Gardiners clay retard the movement of water into the deep confined aquifer below. Also, discontinuous bodies of relatively impermeable material retard movement of water between the shallow unconfined aquifer and the principal aquifer. Perched water zones, fairly widespread in the northern part of the area, are chiefly associated with the till deposits north of the moraines and with clay-bottomed kettle holes within and slightly south of the moraines. Perched water bodies are not tapped by wells within the project area.

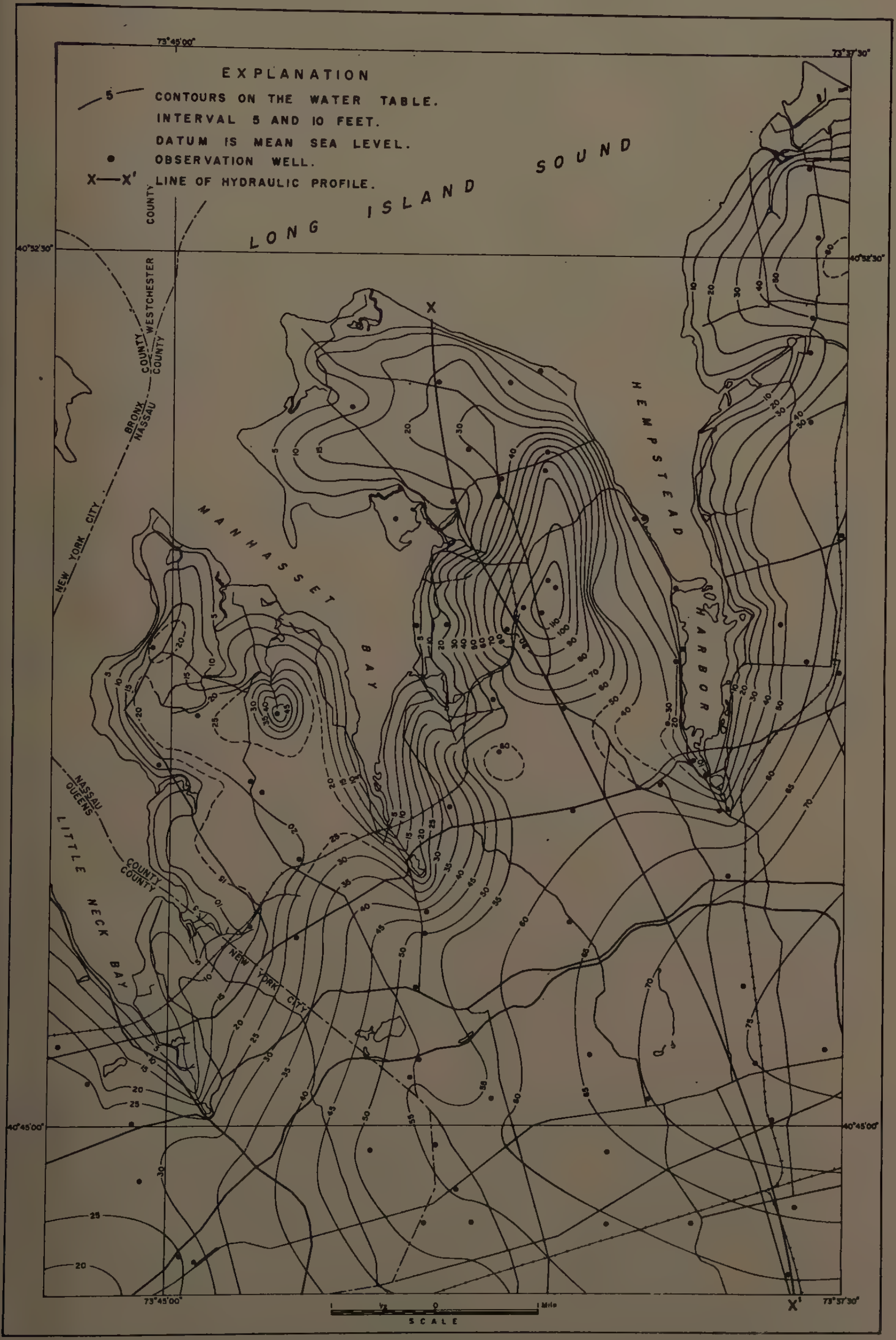

FIGURE 5. Map of northwestern Nassau County, N. Y., showing contours on the water table of the shallow unconfined aquifer in April 1957.

The shallow unconfined aquifer consists of those Pleistocene and Cretaceous deposits that lie within the upper part of the zone of saturation, from slightly below sea level to a little more than 100 feet above. The shallow unconfined aquifer is an important source of water where it occurs in sand and gravel deposits, particularly in the glacial outwash plain south of the Harbor Hill terminal moraine. Individual wells yield as much as 1200 gallons per minute (gpm), and specific capacities as high as 98 gpm per foot of drawdown have been reported for some wells. The shallow unconfined aquifer extends across the water-table divide, from which water flows to the northwest, west, and southwest (FIGURE 5). Gradients near the divide are about 6 feet per mile, and they increase near the shore areas to 25 or 30 feet per mile and locally more. The high altitude of the water table in Port Washington is due to the presence within the aquifer of rather impermeable till zones and Cretaceous deposits, the latter occurring as erosion remnants and ice-shoved masses. Owing to the irregular distribution of these deposits of low permeability, water-bearing zones are discontinuous and less predictable than elsewhere.

The principal aquifer corresponds approximately to that part of the Magothy(?) formation that occurs from about 50 feet below sea level downward to the top of the clay member of the Raritan formation; in places, however, the aquifer includes Pleistocene sand and gravel at the top. Some pre-Wisconsin channels cut to or slightly into the clay member of the Raritan formation and filled with undifferentiated Pleistocene deposits have been noted (FIGURES 2, 3, and 4), and the presence of others can be assumed. This channel fill is generally coarser than the adjacent Magothy(?) deposits with which it is hydraulically continuous. The principal aquifer terminates in the center of the Great and Manhasset Necks, somewhat south of the northern limit of the Cretaceous deposits shown in FIGURE 4. The presence of the clay member of the Raritan formation near sea level limits the extent of the principal aquifer in a northerly direction; beyond its boundary, only the shallow unconfined and deep confined aquifers can be discerned. The principal aquifer is recharged by downward movement of water from the shallow unconfined aquifer through the zone that includes clay lenses of both the Magothy(?) and the Pleistocene. Most of the water pumped for public supply is obtained from the basal Magothy(?) formation within the principal aquifer. Some wells yield up to 1,400 gpm, with specific capacities of 15 to 25 gpm per foot of drawdown. Toward the northern limit of the aquifer, yields are usually below 500 gpm, and the best wells are screened within the Pleistocene channel fill. Ground-water flow is generally in a westerly and northerly direction, not everywhere coinciding with the flow direction in the shallow unconfined aquifer. However, gradients are generally similar in both aquifers. The piezometric contours of the principal aquifer indicate some flow toward the north-shore harbors. Pressure heads in wells along the shore are usually higher than the water-table altitude at the same site, indicating an upward component of flow. Upward leakage of fresh water into the bay areas or Long Island Sound also takes place to some extent, but is impeded by recent bay deposits of silt and clay, and also by local occurrences of the Gardiners clay.

The deep confined aquifer occurs beneath the entire project area, where it consists of the Lloyd sand member of the Raritan formation and the Jameco

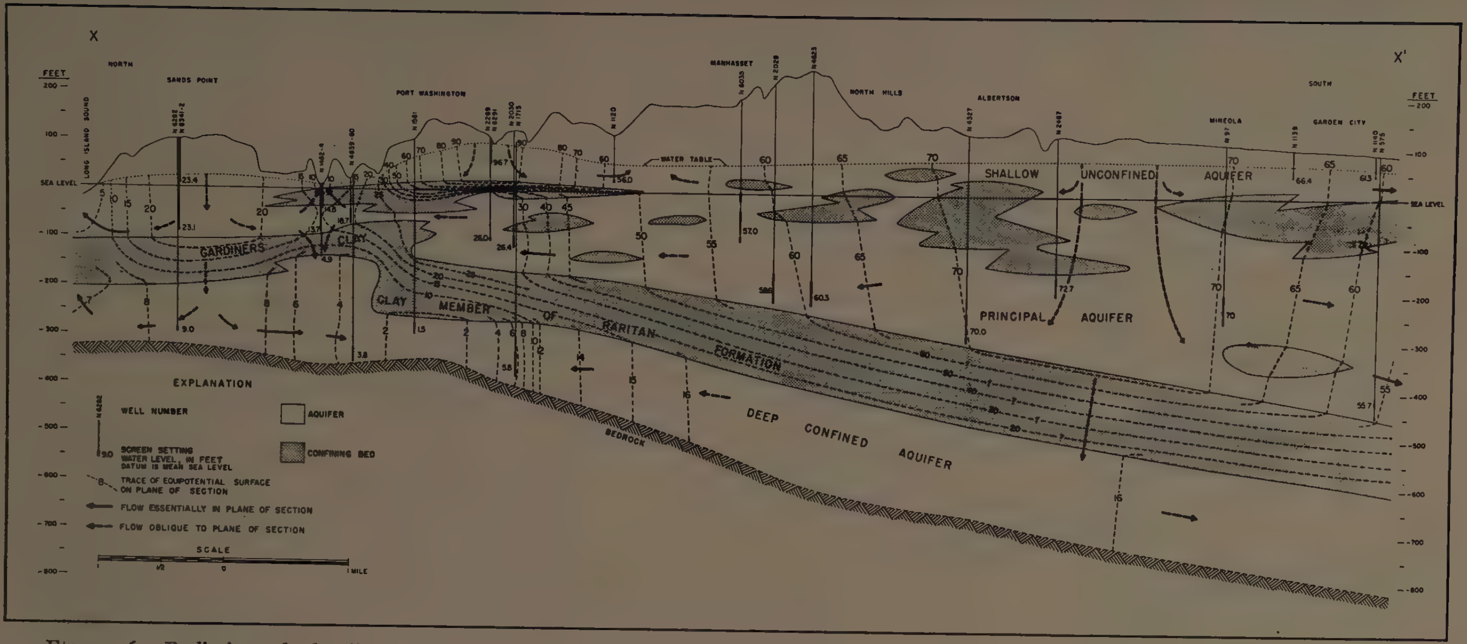

FIGURE 6. Preliminary hydraulic profile through ground-water reservoir along line X-X′ from Sands Point to Garden City, N. Y., April 1957.

gravel. The lower limit of the aquifer is the bedrock surface; its upper limit is the clay member of the Raritan formation and the Gardiners clay, the latter abutting the clay member on the north, or in some valleys and embayments lying directly upon the clay member. The two contiguous clay bodies constitute an effective confining bed that probably extends beyond the shore. The deep confined aquifer is a truly artesian aquifer in which pumping effects are widespread and observed piezometric heads reflect withdrawals from wells both within and beyond the project area. Flow is generally in a westerly direction, at gradients that are about 2 to 3 feet per mile except near pumping wells. Recharge to the deep confined aquifer occurs by lateral flow within the aquifer from the east, beyond the project area, and by downward leakage of water through the confining beds from the aquifers above. The deep confined aquifer is an important source of water along the north shore of Long Island, and locally is the only available source for large supplies. Public-supply withdrawals from the aquifer in the project area in 1957 totaled 4.5 mgd, mostly in the Great Neck and Manhasset Neck areas.

Figure 6 is a preliminary hydraulic profile through the ground-water reservoir of northwestern Nassau County, showing the aquifers and chief confining strata, head relationships, and principal areas of recharge and discharge. Water levels and piezometric heads are given as of April 1957 and reflect, where measured in supply wells, average recovery periods of 8 to 12 hours after pump shutdown. The line of profile was chosen to show principal head relationships and flow directions in the reservoir. Inasmuch as flow directions in shallow and deep aquifers do not entirely coincide in any one plane of section, some oblique flow components are necessarily included and labeled as such.

Conclusion

In general, ground-water supplies in sufficient quantity and of excellent quality for most uses can be obtained from the various aquifers underlying northwestern Nassau County. Ground-water withdrawals for public supply increased with population growth from 9.8 mgd in 1940 to 30.1 mgd in 1957. In addition, about 10 mgd is pumped for various industrial, private, and institutional uses. Although much of the water pumped for industrial purposes is returned to the ground through diffusion wells and recharge basins, an increasing amount of water is lost from the reservoir by the expansion of sewer systems discharging to tidewater.

The eastern and southeastern parts of the area, where natural recharge is at a maximum, offer the largest potentialities for future increased withdrawals. In an area circumscribed by the 60-foot contour on the water table, including the ground-water divide, no changes other than fluctuations attributable to precipitation patterns have occurred in the position of the water table since 1903. Peripherally, toward the southwest, water levels have declined about 15 feet as a result of heavy withdrawals in central Queens. A limited increase of withdrawals in the area outlined above probably would not alter the position of the water table appreciably. Moreover, within limits not yet ascertained, additional withdrawals would increase gradients and induce greater ground-water flow from adjacent, essentially untapped sources to the east, without detrimental effects on the ground-water reservoir.

Locally, ground-water resources approach full development, particularly in the Great Neck and Manhasset Neck areas. The chief limiting factor lies in the geometry of the aquifers and the reduction in thickness of saturated sediments. In the northern parts of both peninsulas the reservoir is less than 400 feet thick, and locally up to 75 per cent of it consists of silt and clay. A further problem lies in the distribution of wells screened in the deep confined aquifer along the shore. Salt-water encroachment resulting from excessive pumping has occurred in one locality in Port Washington. The danger of salt-water encroachment is ever present in other shore areas, as evidenced by chloride concentrations in some wells that are higher than normal even though the water is still usable.

Summary

In cooperation with the Nassau County Department of Public Works and the New York State Water Power and Control Commission, the United States Geological Survey has completed the field work of a rather detailed investigation of geology and ground-water occurrence in northwestern Nassau County, N. Y. The area, approximately 63 square miles, includes the peninsulas called Great Neck and Manhasset Neck, the western part of Nassau County as far south as Garden City, and a small area in northeastern Queens. Unconsolidated sediments of Pleistocene and Cretaceous age, 200 to 800 feet in total thickness, constitute the ground-water reservoir of the area. Detailed study of well logs has revealed the presence of Pleistocene and pre-Pleistocene channels cut in the Cretaceous deposits and in bedrock beneath the Cretaceous. The locations and dimensions of the channels and the character of the subsequent Pleistocene fill markedly affect the pattern of ground-water circulation. The ground-water reservoir contains three discrete aquifers, not all found in the same area, which transect geologic boundaries. The shallow unconfined aquifer occurs essentially in upper Pleistocene deposits; the principal aquifer includes some of the older Pleistocene deposits, but consists principally of the Magothy(?) formation of Late Cretaceous age; and the deep confined aquifer is in the Jameco gravel and the Lloyd sand member of the Raritan formation of Late Cretaceous age. During 1957 the total withdrawals of water for public supply amounted to 30 million gallons per day, of which 72 per cent was pumped from the principal aquifer.

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STRUCTURE SECTION ACROSS THE HUDSON RIVER AT NYACK, N. Y., FROM SEISMIC OBSERVATIONS*

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Introduction

During the summer of 1950 a series of seismic refraction measurements was made in the Hudson River between south Nyack and Tarrytown, N. Y. This work was done as part of the preliminary investigation of foundation conditions for the Tappan Zee Bridge of the New York Thruway Authority at Tarrytown.

Approximately half of the seismic profiles were shot along the bridge line with an east-west orientation. The other profiles were observed across the bridge line and oriented roughly north-south. The latter were necessary since changes in slope or velocity tended to occur along the course of the river and so that the profiles, in some instances, could be made sufficiently long to determine the configuration of the deeper layers.

An extensive boring program was also carried out as part of the preliminary investigations. A total of 34 holes, some extending as deep as 340 feet from the water surface, were drilled at intervals along the bridge line. By comparing the seismic results with the borehole information it was possible to identify the seismic horizons with their geologic equivalents.

The seismic investigations were undertaken for the New York Thruway Authority. Financial support for the project was obtained through a grant from the consulting engineers for the Thruway.† The work was done with two small boats, a 38-foot picket boat and a 42-foot motor torpedo retriever, provided as government-furnished equipment by the United States Navy. The explosives used were from surplus navy stores. The communication equipment and the apparatus for recording the seismic waves were provided by Columbia University, New York, N. Y. W. C. Beckmann, J. E. Oliver, T. Aldrich, and M. Cassidy participated in the field program.

General Description

The Tappan Zee Bridge stretches between south Nyack, New York, and a point just south of Tarrytown, N. Y. The Hudson River here is almost three miles wide (FIGURE 1). Over the greater part of this distance the water is fairly shallow and reaches depths in excess of 20 feet only in the channel on the eastern side. The maximum depth in the center of the channel is slightly over 40 feet.

All of the seismic data are shown, although some of them were not used in the final determinations of the structure. The recording stations are marked with small circles, and the lines extending from these indicate the directions in which and the distances for which shots were fired from these points.

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* Lamont Geological Observatory, Columbia University, Contribution No. 291.
† Madigan-Hyland, Long Island City, N. Y.

A selected number of borehole locations is also shown on FIGURE 1. These are the ones used to describe the upper layers in FIGURE 3. A total of 34 holes was drilled, mostly along the bridge line, and the locations of those pertinent to the discussion and not included in FIGURE 1 are given later in the text.

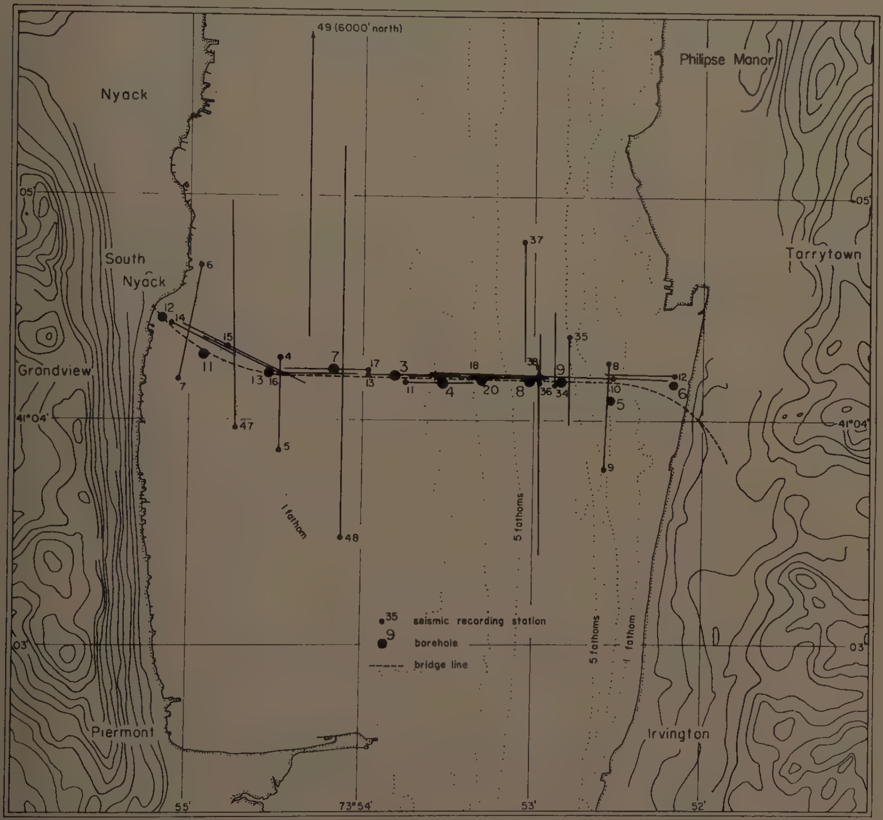


FIGURE 1. Location map.

Methods of Investigation

The 38-foot picket boat was equipped for receiving the seismic shots since it had a cabin which could be made light-tight. A 12-channel seismic refraction system* was installed, and the signals were picked up by 6 geophones and 2 hydrophones. The geophones were pushed into the soft mud of the bottom at 100-foot intervals, with the recording boat in the center of the spread. Two channels of the recording system were modified to pass the high-frequency signals through the water, which were picked up by the hydrophones. The latter were located at the position of the recording boat. The radio receiver was connected to one trace of the recording oscillograph so that the instant of

* Century Geophysical Company, Tulsa, Okla.

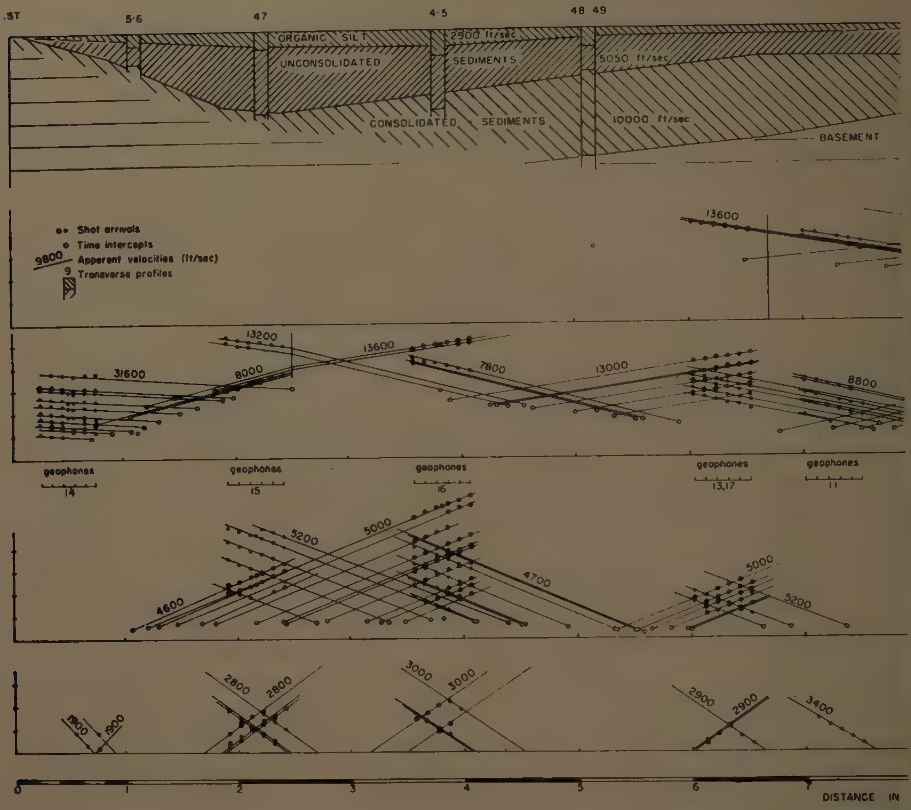


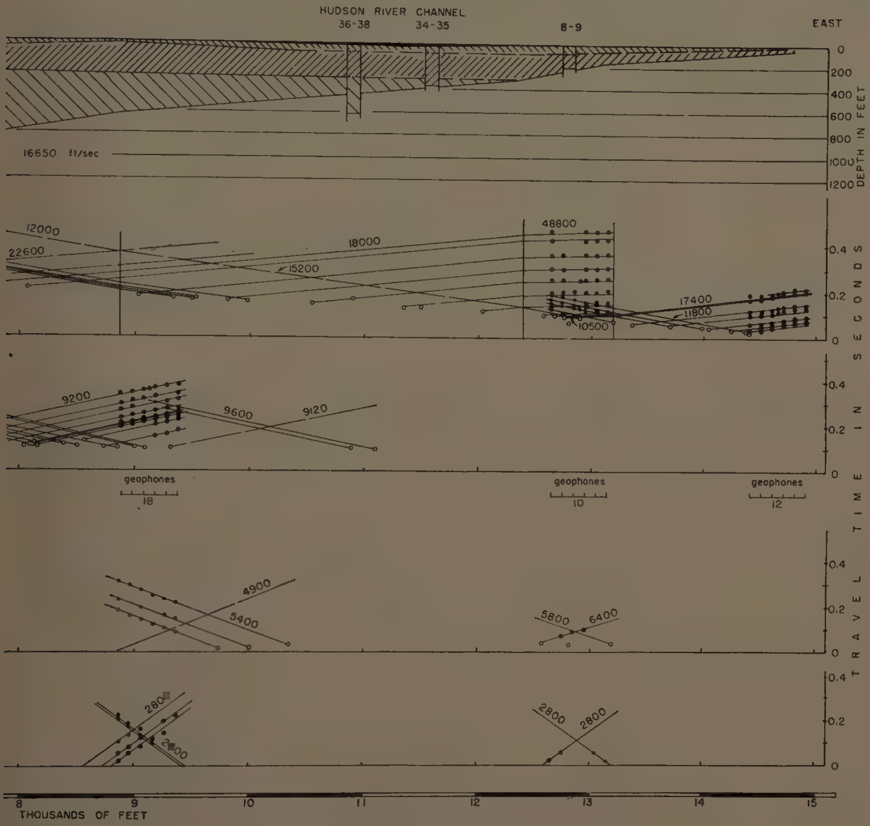
FIGURE 2. Travel-time

firing, transmitted by the shot boat, could be placed on the same record as the sound arrivals.

The shot boat was equipped to fire charges electrically, and also had an FM radio for communications. The charges were made of TNT or tetryl, and varied in size from a detonating cap to 24 pounds.

In practice, the picket boat was anchored bow and stern at the desired recording position and the geophones pushed into the mud with a long pole. The position of the boat was determined by horizontal sextant angles on shore landmarks; then the shot boat moved out along the prescribed line, firing the necessary charges. In the center of the channel, where it was not possible to push the geophones into the mud, geophones were placed in an orienting frame and set on the bottom. Due to the strength of the current, it was not possible to work in the channel except during slack water.

Early in the investigations distances were measured by use of a taut-wire method, and stakes were planted where the shots were to be fired. From these measurements the velocity of sound in the river water was determined to be 4825 fps, a value in good agreement with that later calculated from



curves and seismic section.

temperature-salinity measurements. This value, together with water-wave travel times, was used to determine distances for the remainder of the program.

Interpretation of Data

The seismic refraction data are presented in the form of travel-time curves, with the travel times of the waves through the different layers as the ordinates and distances as the abscissae (FIGURE 2). In the interests of clarity, the lines for the different layers have been separated on the travel-time graphs, with the lines for the uppermost layers plotted at the bottom.

The method of calculation of dip, depth, and velocity of the layers from the slopes and zero-distance intercepts of these lines has been described in Ewing *et al.* (1939), as well as in various textbooks on explosion seismology. The method assumes that the different layers are planar within the extent of a profile. It was necessary to modify it slightly when changes in slope occurred. This modification involves a division of the profile into parts at the point where the change of slope occurs, and has been described in Ewing *et al.* (1950) and Oliver and Drake (1951).

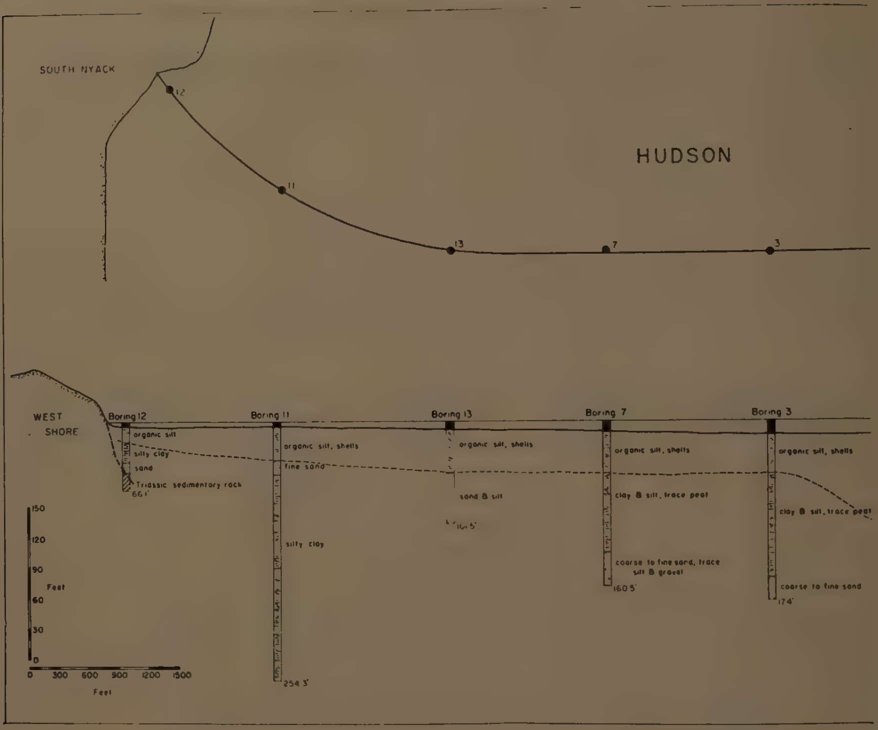


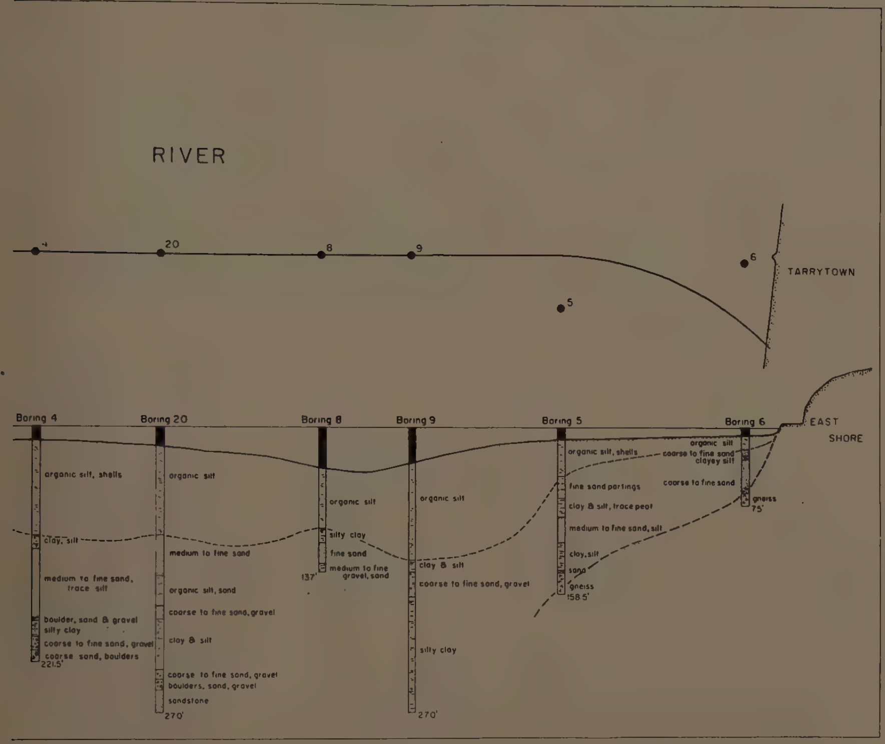
FIGURE 3. Upper layers

Discussion of Results

The seismic velocity in the sediment at the river bottom was considerably less than that in water, and averaged 2900 fps (TABLE 1). This low velocity suggested a high content of organic material or the presence of included gases in the sediment. Both factors contributed in this case. The borehole information (FIGURE 3) showed that the uppermost sediment layer is an organic silt, with some shells, while gas bubbled to the surface each time the bottom was disturbed, as in the planting of geophones. The sound transmission properties of this material were, as a result, quite poor, especially for the higher frequencies. This meant that larger charges were required than otherwise might be the case, but it had the advantage that the water waves were attenuated sufficiently that the later arrivals from this layer could usually be seen.

No layering was indicated in the remainder of the unconsolidated sediments. These are grouped in a single layer with an average velocity of 5050 fps (TABLES 2 and 3). The sediments include sands, silts, clays, and gravels, with an occasional boulder. The location of the boundary between this layer and the overlying organic silt as determined by the borings was not always the same as that indicated by the seismic results.

Below this, on the western side of the river, a layer with a mean velocity of



from borehole data.

10,000 fps was found. This velocity is appropriate for consolidated sediments, and the layer has been identified with the Triassic sedimentary rocks in several of the boreholes. Similar velocities were found in Triassic sediments in Park Ridge and Livingston, N. J. in shallow seismic investigations, and laboratory measurements of a sample of Triassic sandstone yielded the same results.

The deepest layer encountered, with a mean velocity of 16,650 fps was identified by boreholes on the eastern side of the river with the metamorphic and intrusive rocks of Westchester County. This velocity is appropriate for such rocks, and similar velocities have been observed in other investigations, both marine and on land, in this general area.

A standard section was adopted for the calculations and is shown in FIGURE 4. In most cases large velocity differences from this standard were due to changes in slope or structure. In a few cases the velocity differences are due to real changes within a layer. The observed velocities were used rather than the mean where this was true.

Structure Section

A structure section across the river based principally on the seismic information is given at the top of FIGURE 2. After the seismic work was completed a number of supplementary boreholes were drilled that allowed greater detail to be shown for some of the layers. Among these holes were a number that reached bedrock, either the metamorphics or the Triassic sedimentary rocks, and determined its upper surface from the eastern bank almost to the middle of the river. A structure section based on all the data is given in FIGURE 5.

The upper surface of the metamorphic basement slopes to the west at a 5° to 10° angle and shows only minor relief. Where encountered in boreholes, it has been identified as gneiss and may be identified with the Yonkers gneiss found on the adjacent shore. The gneiss was relatively unweathered and difficult to drill except in hole 16, where its disintegrated nature suggests the presence of a fault zone (FIGURE 5).

The Triassic sedimentary rocks above this extend as far as the present channel, well over on the east side of the river. These have a dip, on the western bank of the river, of about 10° and, unless they are faulted, reach a thickness in excess of 1500 feet. This is somewhat thicker than in the New York City area where the thickness is more nearly 600 feet. Perhaps the most significant feature of the structure section is the deep channel, reaching 740 feet, which is cut into these beds near the west bank of the river. Although there is no assurance that the position of this channel was not determined by a fault or a line of weakness, neither is there any need to call upon faulting to explain its presence.

TABLE 1

SEISMIC VELOCITY IN THE FIRST LAYER

Seismic station	Velocity fps	Seismic station	Velocity fps
4	—	16E	3000
5	3000	16W	3000
6	—	17	2900
7	—	18E	2800
8	2800	18W	2800
9	3000	34	—
10E	2800	35	—
10W	2800	36	—
11	3400	37	3000
12	—	38	—
13	2900	47	—
14E	1900	48	—
14W	1900	49	—
15E	2800		
15W	2800		

Key: 2855, mean; 2920 mean neglecting 14E and 14W; 2900, adopted value.

The Triassic sedimentary rocks and the basement are covered by unconsolidated sedimentary rocks varying in thickness from a few feet to more than 500 feet. These consist of clays, silts, and sands with some gravel and an occasional boulder. In those holes that penetrated the Triassic rocks there was usually a zone of reddish-brown sand and gravel immediately above the contact that suggested weathered Triassic material.

The organic silt layer at the top of the geologic column tends to be somewhat

TABLE 2
OBSERVED VELOCITIES AND TIME INTERCEPTS

Seismic station	V_{2a}	V_{2b}	V_{3a}	V_{3b}	V_{4a}	V_{4b}	T_2	T_3	T_4	Location of time intercept
Transverse Profiles										
6-7a	7000		15,000				0.080	0.148		SS 6
b	4500		8600				0.129	0.150		800 ft. south of SS 6
c		5700		10,600			0.055	0.140	0.275 min.	at shot 112 more than 800 ft. north of SS 7
47	5500		12,000				0.090	0.293	0.41 min.	SS47
4-5	5000	5300	10,800	10,800			0.086	0.300	0.40 min.	bridge line
48-49			10,200	11,000	17,600	21,200	0.045a	0.196	0.323	bridge line
36, 38-37					17,600	16,000		0.100a	0.168	bridge line
34-35					19,500	13,400	0.030a		0.136	bridge line
8-9a	7200	4800			25,500	11,000	0.035		0.068	bridge line
b	not detected				17,800	15,300	—		0.112	SS9
Bridge Line Profiles										
15	5200	4600	13,200	8000			0.075	—		SS15
16	4700	5000	7800	13,600			0.085	0.250		SS16
13, 17	5200	5000	9600	13,000	13,600		0.041	0.153	—	SS13, 17
11-18	—	—	8800	9,200	12,000	22,600	—	0.108	0.234	SS11
18	5400	4900					0.013			SS18
18-channel	—	—	9600	9,120	15,200	18,800	—	0.100	0.150	at st. 285 (10,350 from west bank)
10	5800	6400	none		10,500	48,800	0.040	—	0.088	SS10
12	—	—	none		11,600	17,400	—	—	0.023	SS12
at shot 196							—	0.128		Shot 196 (1065 from west bank)

Subscript *a* means this value was assumed from the bridge line data.
Key: V in fps., T in sec.

TABLE 3

VELOCITIES, THICKNESSES, AND SLOPES OF LAYERS

Seismic station	V_2	V_3	V_4	h_1	h_2	h_3	h_w	W_{12}	W_{23}	W_{34}
Transverse Profiles										
6–7a	5050*	10,000*		141	161		5	+10.50	−10.80	
b	5050*	10,000*	16,350*	238	0		5	−5.00	+4.10	
c	5050*	10,000*		97	222		5	−4.45	+6.90	
47	5050*	10,000	16,350*	168	576		5	−3.20	+0.70	
4–5	5140	10,800	16,350*	243	474		5	−1.20	+2.35	
48–49	5050*	10,550	19,200	182	167	853	6	0*	−1.20	−0.55
36, 38–37	5600*	—	16,900	50*	226	352	34	0*	0*	−2.40
34–35	5600	—	15,800	51	—	301	38	0	—	+3.90
8–9a	5700	—	15,400	59	—	86	8	+6.60	—	−4.75
b	—	—	16,500	—	—	165	8	—	—	+0.8
Bridge Line Profiles										
−15	4900	9920		136	—		5	+2.55	+5.75	
−16	4830	9700		154	414		5	−1.25	−6.15	
−13, 17	5080	11,300	16,340*	72	333	—	7	+0.70	−4.80	−0.80
11–18	5050*	9000	15,450	70*	189	641	8–14	−1.60	+2.45	−11.25
18	5150			22			14	+1.90		
18 channel	5600*	9350	16,900	50*	238	202	14–39	+1.00*	−1.15	−6.45
−10	6050	none	16,950	66	—	129	15–8	−1.50	—	−10.70
−12	6050*	none	13,850	15*	—	44	8–3	−1.50*	—	−2.15
at shot 196	5050*	10,000*		80*	220†			0*	0*	

Key: V in fps., *h* in feet, *w* in degrees. Subscript 1 is top seismic layer. Subscript 12 is interface between layer and layer. The symbol + is upslope to N on transverse profiles and upslope to W on bridge line profiles.

* Mean value was assumed by interpolation.

† Estimated.

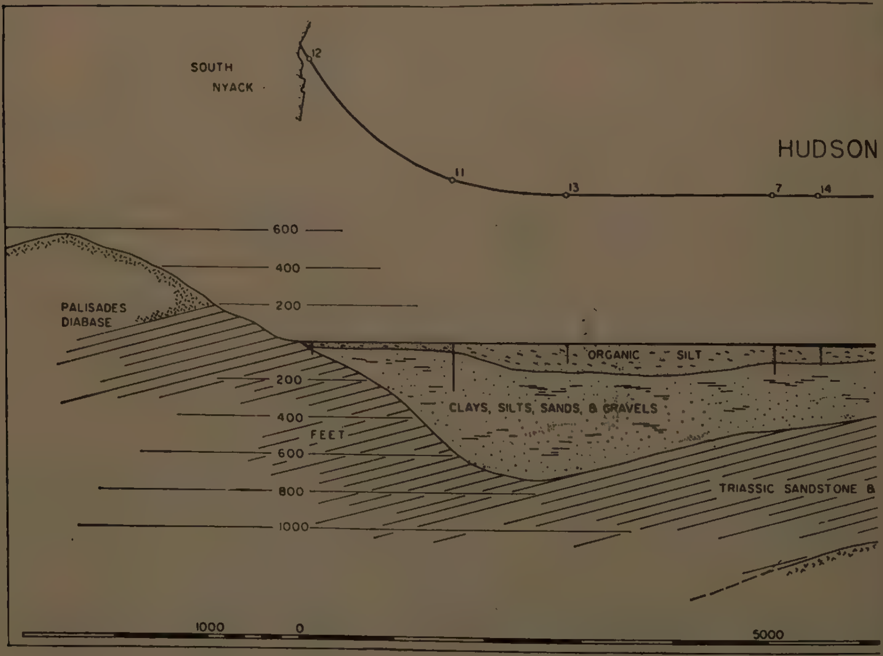


FIGURE 5. Structure section

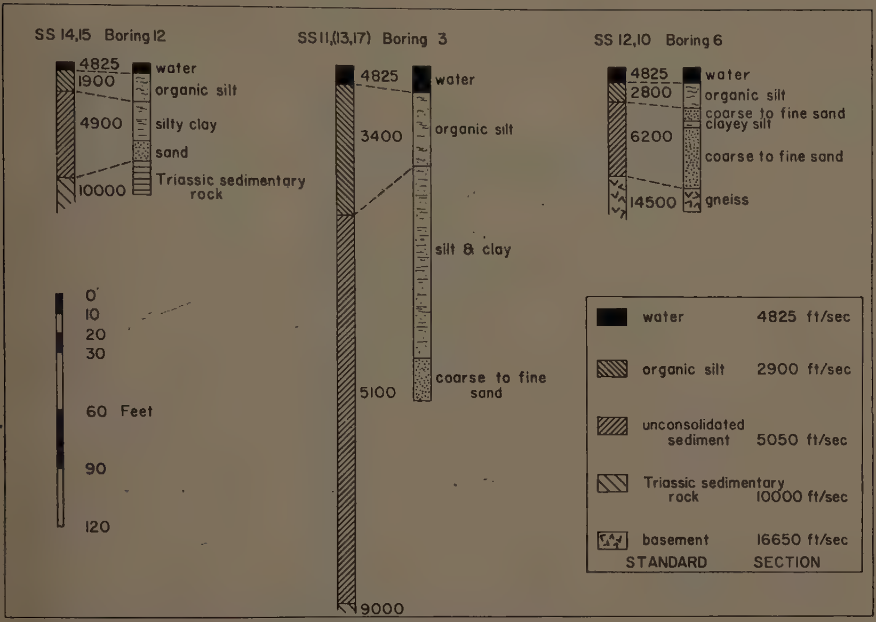
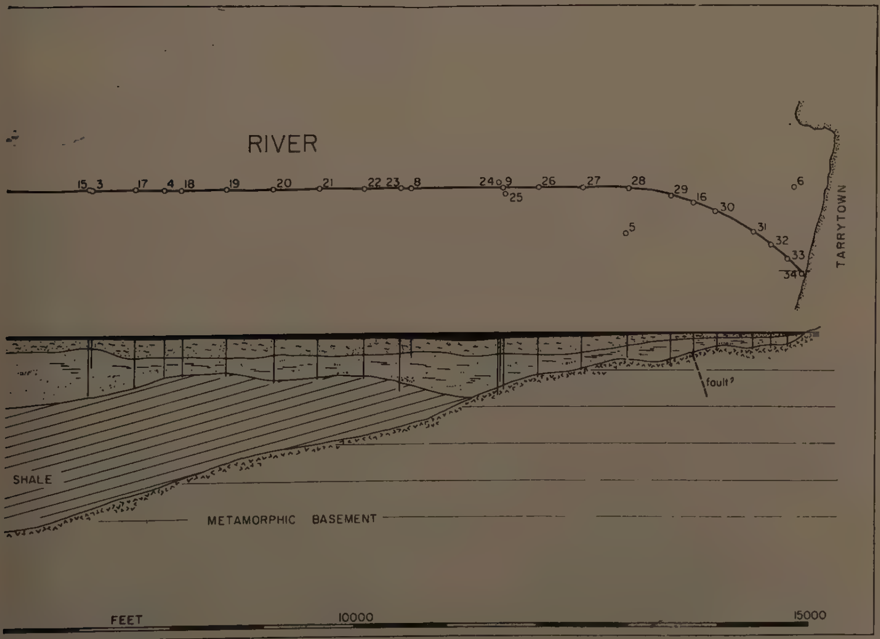


FIGURE 4. Identification of seismic horizons and standard section.



from seismic and borehole data.

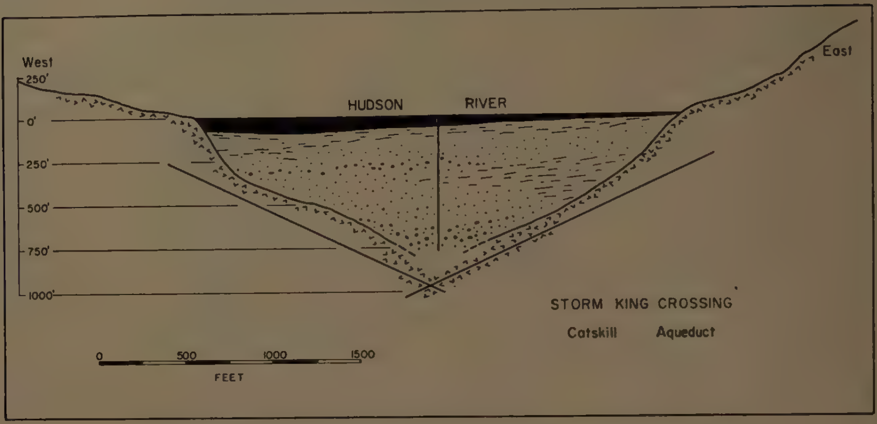


FIGURE 6. Structure section: Storm King. After Berkey, 1933.

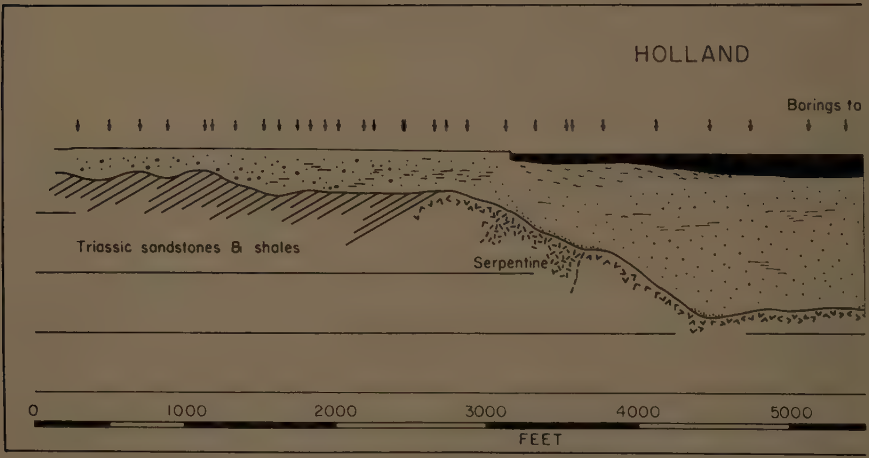


FIGURE 8. Structure section: Holland Tunnel.

thicker over the deep channel to the west and under the present channel, and reaches a maximum of about 140 feet. The shells found in this layer are remnants of once prolific oyster beds. At the present time there is no active harvesting of oysters, although the shell at the surface is used for seeding oysters which are later transported to Long Island Sound to mature.

Comparison with Other Sections and Geological Implications

Numerous borings were made in connection with the pressure tunnel under the Hudson River which was constructed as a part of the Catskill Aqueduct.

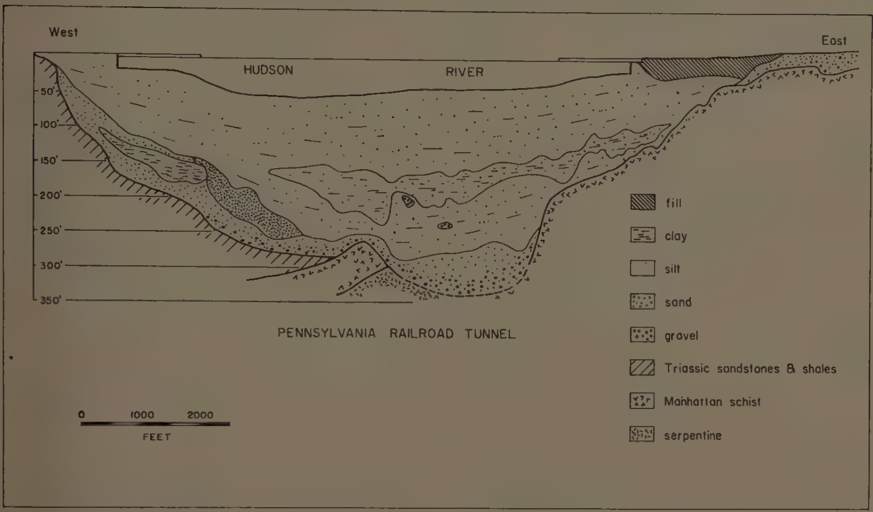
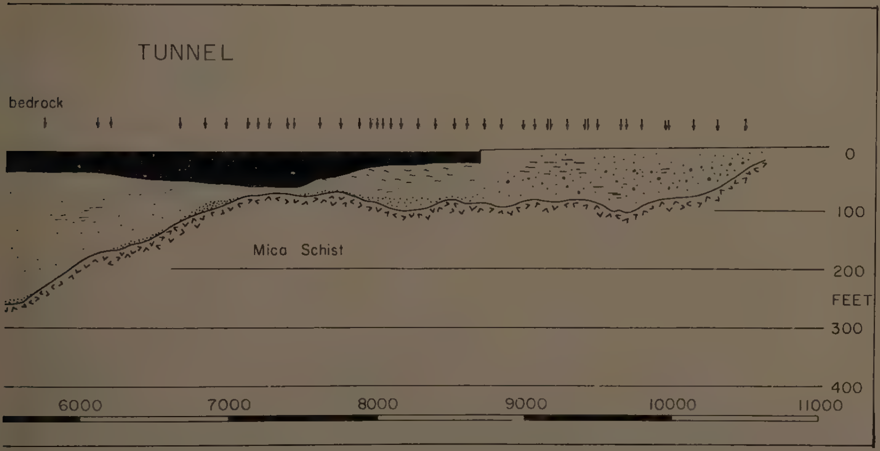


FIGURE 7. Structure section: Pennsylvania Railroad tunnel. After Berkey, 1948.



After *Rock Data Map of Manhattan,* 1940.

Great difficulty was encountered in drilling vertically from the river due to currents, river traffic, and the presence of boulders. In spite of this, one hole was carried to a depth of 765 feet without encountering bedrock (FIGURE 6). Diamond-drill holes were later made from working shafts on either side of the river. These slanted under the river and intersected at a depth of 950 feet. The depth of the buried channel here is between these two depths and somewhat deeper than at the Tappan Zee Bridge.

A seismic profile was observed in the river about three miles north of the Tappan Zee Bridge in 1954. This profile reached the Triassic sedimentary rocks at a depth of 760 feet and confirmed the results of the earlier work.

The velocity in the organic silt was even lower at this location, measuring 1770 fps.

South of the bridge the depth has not been positively ascertained. The borings made for the Pennsylvania Railroad tunnel (FIGURE 7) reach bedrock everywhere except for a 2500-foot section in the middle of the river. The section constructed by Berkey (1948) suggests that the maximum depth of the buried channel here is about 350 feet, but there is the possibility that a narrow gorge extends deeper.

Numerous borings have been made along the length of the Holland Tunnel.* The maximum depth to bedrock was reached on the western side of the river at approximately 290 feet (FIGURE 8). Since the distance between adjacent borings along this line is not more than 750 feet, the possibility of a narrow deep channel being present is decreased further.

These sections indicate that there is a reversal of the gradient of the deep buried channel between Storm King and New York City. This reversal would be increased in magnitude if postglacial uplift of those areas covered by ice during the Pleistocene were considered.

Reversals of gradient are common in fiords and valley glaciers which customarily have sills near the downstream extremities at a shallower depth than the base of the valley upstream. It is well known that the Pleistocene glaciation extended as far south as New York City. Numerous glacial deposits are found on both sides of the Hudson River, and glacial striations are found on top of the Palisades in New Jersey and New York and on the rocks of Westchester County and Manhattan. The Narrows is cut through the terminal moraine, which extends from Staten Island through Brooklyn.

It is probable that the deep, buried channel was cut by the ice during the Pleistocene. The cliffs of the Palisades were likely cut at the same time. The depth of the channel in the Narrows should be considerably less than that at Nyack, and it reflects sea-level change during the Pleistocene rather than glacial activity.

Summary and Conclusions

The data from twenty-three seismic refraction profiles and thirty-four boreholes made as a part of the preliminary investigations of foundation conditions at the Tappan Zee Bridge were combined to construct a structure section across the Hudson River. Four seismic horizons were identified with organic silt, unconsolidated sediment, Triassic sedimentary rocks, and the metamorphic and intrusive rocks of Westchester County.

The structure is, in general, that which would be predicted from a study of the geology of the adjacent shore lines. Although no evidence of a large fault determining the course of the Hudson River was found, the possibility of such a fault with a throw of a few hundred feet is present. Perhaps the outstanding feature of the section is a buried channel on the west side of the river that reaches a depth of about 740 feet. Comparisons with sections at Storm King and New York City indicate a reversal in gradient within this channel. It is suggested that this reversal was caused by the Pleistocene ice sheet which covered the area.

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* *Rock Data Map of Manhattan* prepared by the staff of the borough president and revised in 1940, unpublished.

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THE PALISADES RIDGE IN ROCKLAND COUNTY, N. Y.

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INTRODUCTION

The Palisades Ridge (Palisades of the Hudson) consists of a diabase intrusive (sill) that crops out and forms a conspicuous ridge from Bayonne, N. J., northward along the west side of the Hudson River to Haverstraw, N. Y., and thence westward to Mt. Ivy. The diabase is intruded into Triassic sedimentary rocks and is itself presumably of Triassic age.

As indicated by petrographic studies in New Jersey, especially those of Walker (1940), this sill is unique in that it is one of the thickest to have been formed by a single intrusion. The top and bottom portions are fine-grained. A few feet above the bottom occurs a zone rich in olivine, formed by fractional crystallization. Throughout the remaining several hundred feet of thickness the rock has medium to coarse texture. The olivine-rich zone is a band of relative weakness, in which differential weathering saps the overlying columnar blocks.

That part of the ridge here discussed (FIGURE 1) lies in Rockland County, N. Y., and is shown on the Nyack and Haverstraw (7½-minute) and the Ramapo (15-minute) topographic quadrangle maps of the United States Geological Survey.

Apparently the Palisades Ridge in Rockland County, N. Y., has not been so intensively studied and certainly not so thoroughly described as its southward extension in New Jersey. Darton's publication of 1890 and Kümmel's report of 1900 are the main reports on field studies of the region. Both writers reached essentially the same conclusions on the points enumerated below, and both stated that some of their conclusions were based, in part at least, on observations made in New Jersey.

Conclusions reached by Darton and by Kümmel are:

(1) That the vertical offsets of the base of the sill are due to "lateral migration" across the sedimentary beds.

(2) That those sites where the back slope of the ridge is steeper than the dip of the sediments represent the dike that fed the sill, cutting across the sedimentary beds at a high angle.

(3) That westward from Haverstraw to its terminus at Mt. Ivy the ridge consists of a dike, cutting across the bedding of the sediments, at a low angle according to Darton, or possibly in abrupt steps, according to Kümmel.

(4) That gaps in the ridge represent former stream courses. Although cross faults at some of the gaps were mentioned as a possibility, most of them were ruled out for lack of evidence.

Inasmuch as Darton and Kümmel have given adequate general descriptions of the Palisades Ridge in their reports, these will not be repeated here.

My conclusions on the points enumerated above and elaborated below differ from those of Darton and Kümmel partly because I was able to examine some exposures that were not available to them sixty years ago, and partly because I saw some old outcrops that apparently they failed to find. Mainly, however, the difference lies in a different interpretation of the features that all of us must have seen.

BASAL CONTACT OF THE DIABASE AND SEDIMENTS

Where its contact can be seen, the base of the sill is generally conformable with the underlying sediments. At a point about 2 miles north of Nyack, however, the trap cuts across the shale for a vertical distance of at least 30 feet (Darton, pp. 43 to 49). At many other places the base of the sill is clearly offset up or down, in some cases as much as a few hundred feet. As the actual contact is concealed at those sites, any judgment as to whether the discontinuity is due to a "lateral migration" of the trap across the sediments or whether it is a fault displacement must be based on circumstantial evidence.

Both Darton and Kümmel incline strongly toward the stratigraphic or lateral-migration interpretation. Their argument is that, as offset due to lateral migration can be demonstrated in a few places, it can be postulated elsewhere. Darton says, however (p. 44): "Near Piermont there are some suggestions of a fault diagonally from southwest to northeast with downthrow on the eastern side, but its presence could not be established." Also, "In the great hook farther north, near Haverstraw, the ridge is crossed by two depressions, the Long Clove and the Short Clove, of which the topographic configuration suggests dislocation, but no positive evidence of faulting could be obtained." Although Kümmel's text discounts the probability of faulting where there are offsets, his map indicates a definite fault at Sparkill and a questionable one at Trough Hollow. Although not confirmed by his map, his text (p. 45) states: "At Upper Nyack a fault with throw of not less than 10 feet can be seen in a ledge of red shale a little above the river."

Colony (1933, p. 37) states: "The diabase and inclosing sandstone dip 8° to 15° W., and not uncommonly the eastward-facing escarpment is offset and the base of the sill dropped to river level by Triassic faults, which cut across the strike of the formations obliquely. The largest fault of this character lies between Piermont and Sparkill, about two miles north of the boundary line between New York and New Jersey." Colony gives no other evidence of, or information concerning, the faulting.

My interpretation, that faulting is the cause of most of the offsets, is based on topographic evidence; joint spacing, patterns, and attitudes; size, shape and abundance of talus fragments; and certain distinctive fault phenomena. These criteria are discussed below.

Topographic features. At most of the sites of offset the ridge is marked by recesses in the front and notches in the crest. These recesses and notches are clearly the result of differential weathering and erosion along zones of weakness. Contrariwise, where stratigraphic migration of the diabase is seen to occur, the ridge makes a salient and faces the river in a promontory. Apparently these are places of superior resistance. Lateral migration of the intrusion would not cause a zone of weakness; indeed, by sealing fractures, it should heal any weakness that previously might have existed. However, high-angle faulting, with attendant brecciation, is a well-known cause of erosional weakness.

Joint spacing, patterns, and attitudes. The origin of some joints seems to be nondiastrophic. For example, the columnar joints in the Palisade diabase are interpreted as shrinkage cracks developed during cooling of the magma. They form at right angles to the base of the sill, and divide the rock into columns. In the undisturbed portions of the ridge these columns are generally one to three feet in diameter. At right angles to these columnar joints and, therefore, parallel with the base of the sill and perhaps also as the result of shrinkage, are cracks that break the columns at intervals of several feet. Both of these joint patterns—the columnar system perpendicular to the base and the more widely spaced set parallel to the base—are typical of the Palisades sill, as well as of other igneous sheets (FIGURE 2). Other sets and patterns of joints in the diabase must be considered as secondary fractures that have resulted from subsequent diastrophism. The diastrophic fractures are seen at all of the sites of offset where faulting is here inferred.

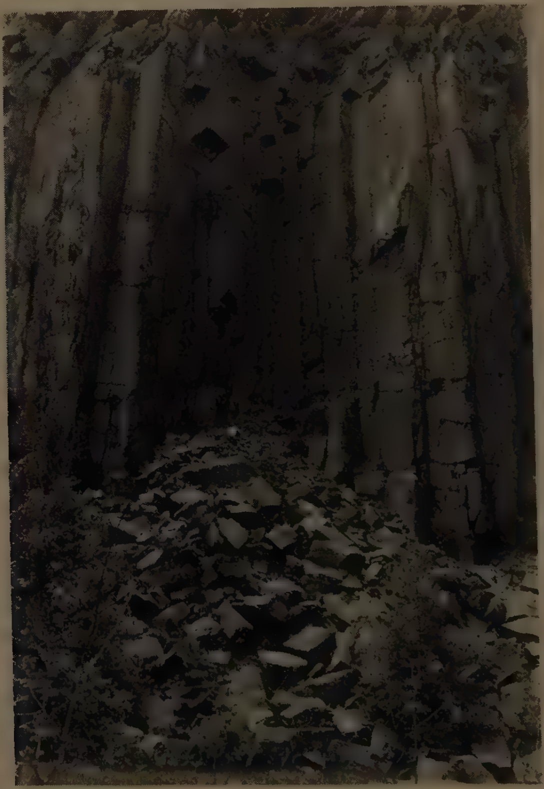

FIGURE 2. Typical columnar and flat-lying tension joints in undisturbed diabase, between Rockland Landing and Trough Hollow. The exposure is about 75 feet high.

The most common secondary fractures observed in the diabase are: (1) a steeply dipping set of platy joints that may be regarded as subsidiary faults parallel to a high-angle normal fault; (2) flat-lying, sheet-like fractures that are typical tension (feather) joints of high-angle reverse faults; and (3) diagonal shear fractures that may accompany either normal or reverse faults (Billings, 1954). In all of these cases the fractures are closely spaced, and the columnar jointing is more or less obscured.

Size, shape, and abundance of talus fragments. The sites of vertical displacement of the sill are marked by more abundant talus than elsewhere. The talus fragments are of much smaller size; also, their shapes are different. Whereas the talus along the straight stretches of the Palisades includes many large blocks that show the columnar form, most of the fragments in and near the gaps are small and many of them are wedge-shaped. They were derived from closely fractured rock. Many old traprock quarries along the river were opened on these shattered rocks.

Fault plane phenomena. At some places where the base of the sill is offset, such fault plane structures as slickensides, breccia, gouge, and mineralized joints can be seen. Where these features are found, faulting is definitely indicated, but they do not tell the amount of displacement. The fact that these features are not now visible at certain suspected fault sites does not establish that they are not, or were never, there, for they may have been removed by erosion or covered with overburden.

THE STRUCTURE SECTION

FIGURE 3 represents the scarp face of the ridge, the profile showing the crest line and the base line drawn at sea level. Where the evidence of faulting seems quite strong, the fault is indicated by a solid line. Where faulting is probable, but the evidence is inconclusive, broken lines are used. Question marks indicate where the direction of movement is not clear. Doubtless the faults are not as straight or simple as the diagram suggests. As the profile follows a sinuous crestline, it is considerably longer than the straight line between its two end points.

Just south of the New York State line the crest of the Palisades ridge descends from an altitude of about 500 feet to about 200 feet, which it maintains for a distance of 2 miles, and then rises to more than 600 feet. This broad gap, the most prominent in the whole ridge, is named from Sparkill Creek, which has cut a still deeper notch in its northern part at Piermont.

Along the river front at Alpine, south of the gap, the sediments crop out at an altitude of more than 200 feet above river level.* From that point northward to Piermont the positions of the base of the sill indicate a graben at Skunk Hollow and another at Sparkill Creek, with a step-faulted horst between them. At each of the precise sites of dislocation the actual plane of displacement is concealed, being either covered with talus or till or both. However, instructive outcrops of the bedrock can be seen nearby.

At Skunk Hollow, the first graben, the base of the sill is below river level.

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* Inasmuch as the Hudson is an estuary throughout the length of the ridge and beyond, reference to river level is synonymous with reference to sea level.

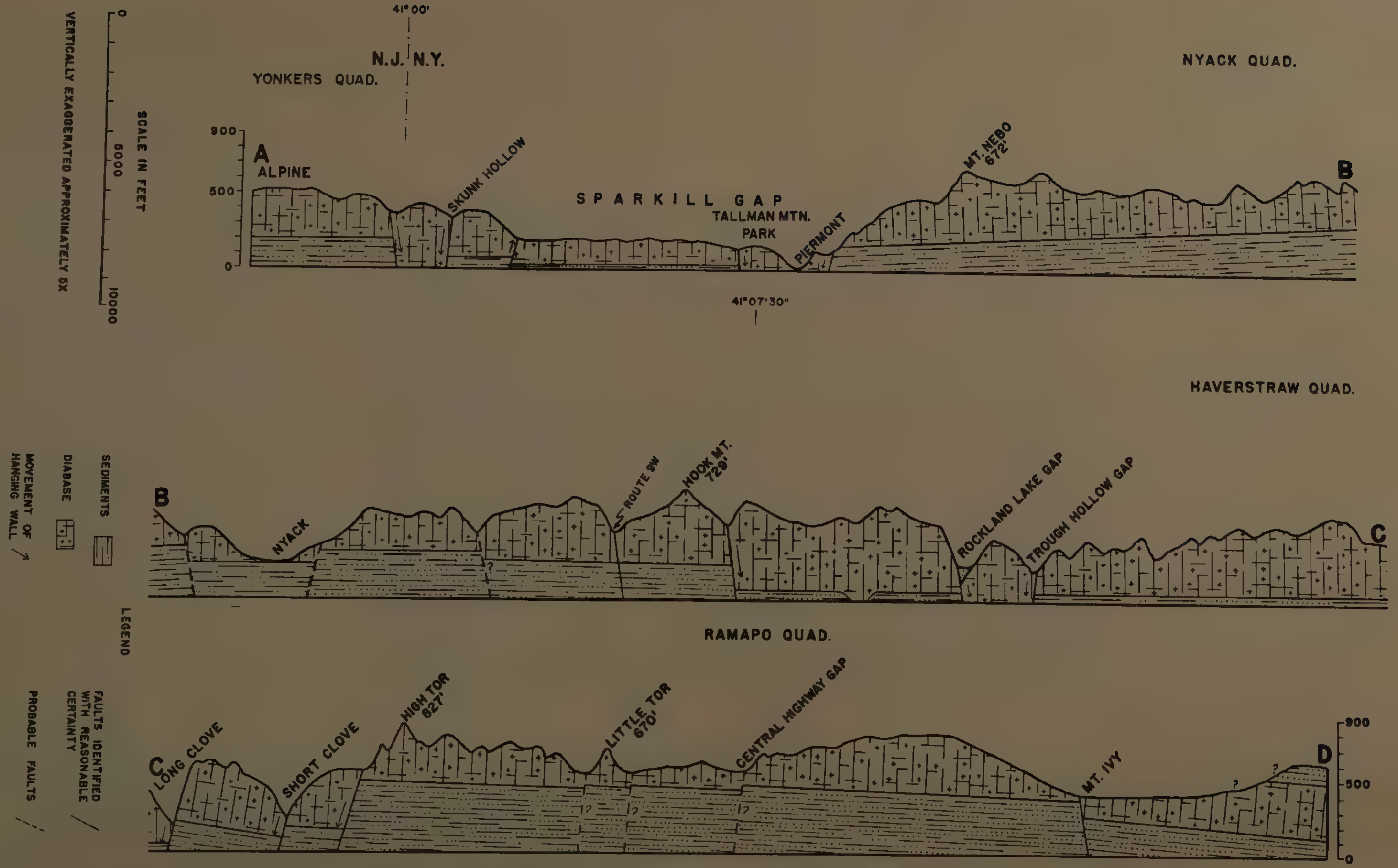

FIGURE 3. Longitudinal profile and structure section of the Palisades Ridge in Rockland County, N. Y.

A few hundred yards to the north the sediments are exposed. The red shales are so badly shattered that they appear to be fault breccia. The more massive overlying arkose beds, though not so badly crushed, show several sets of close fractures, the most prominent of which strikes N 50 to 55 E and dips NW at 60 degrees. If these prominent joints be interpreted as tension fractures (feather joints), they suggest a normal fault with strike N 55 E and dip SE at 75 degrees. Inasmuch as the offset of the sill base here is accompanied by crushed rock and a joint pattern that is harmonious with a steeply dipping normal fault, and also is marked by a notch in the ridge, it seems reasonable to assume faulting at Skunk Hollow.

On the basis of both topography and structure a small graben is indicated. The vertical displacement along the southern fault is at least 200 feet for, just south of it, the underlying sediments stand at an altitude of 200 feet while, in the graben, the base of the diabase is at or below river level.

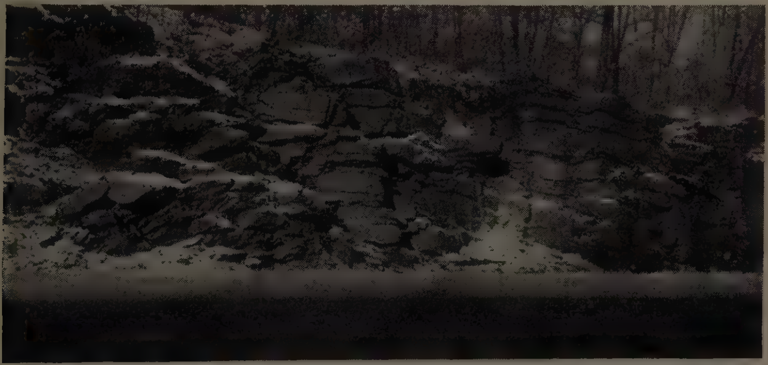

FIGURE 4. Palisade diabase along Route 9W, one-fourth mile north of the New Jersey State line. Columnar joints are obscured by closely spaced, flat-lying joints. The exposure is about 10 feet high.

Just north of this graben the sediments rise abruptly to nearly 100 feet in altitude and crop out along the river. An erosional bench on this outcrop is the site of a number of dwellings in the village of Palisades, N. Y.

A short distance north of Palisades (Sneden) Landing the base of the sill drops down to about 20 feet in altitude and continues north at that level about a mile and a half. Along the river the manner of this change of level is not apparent. However, along Route 9W, as it descends northward, into the broad Sparkill Gap, in topographic line with this change of level, there is an instructive outcrop of the diabase (FIGURE 4). At this site the rock contains numerous low-angle fractures. Such close fracturing is not typical of the undisturbed rock. Whereas the spacing of the normal low-lying primary tension fractures, resulting from cooling of the magma, averages 5 or 6 feet, in these fractures it averages about 6 inches. Most of them must be secondary. My interpretation is that they are feather joints, resulting from high-angle reverse faulting.

In Tallman Mountain Park, in the northern part of Sparkill Gap, a short distance south of the creek, a ravine leads down to the river. On the south

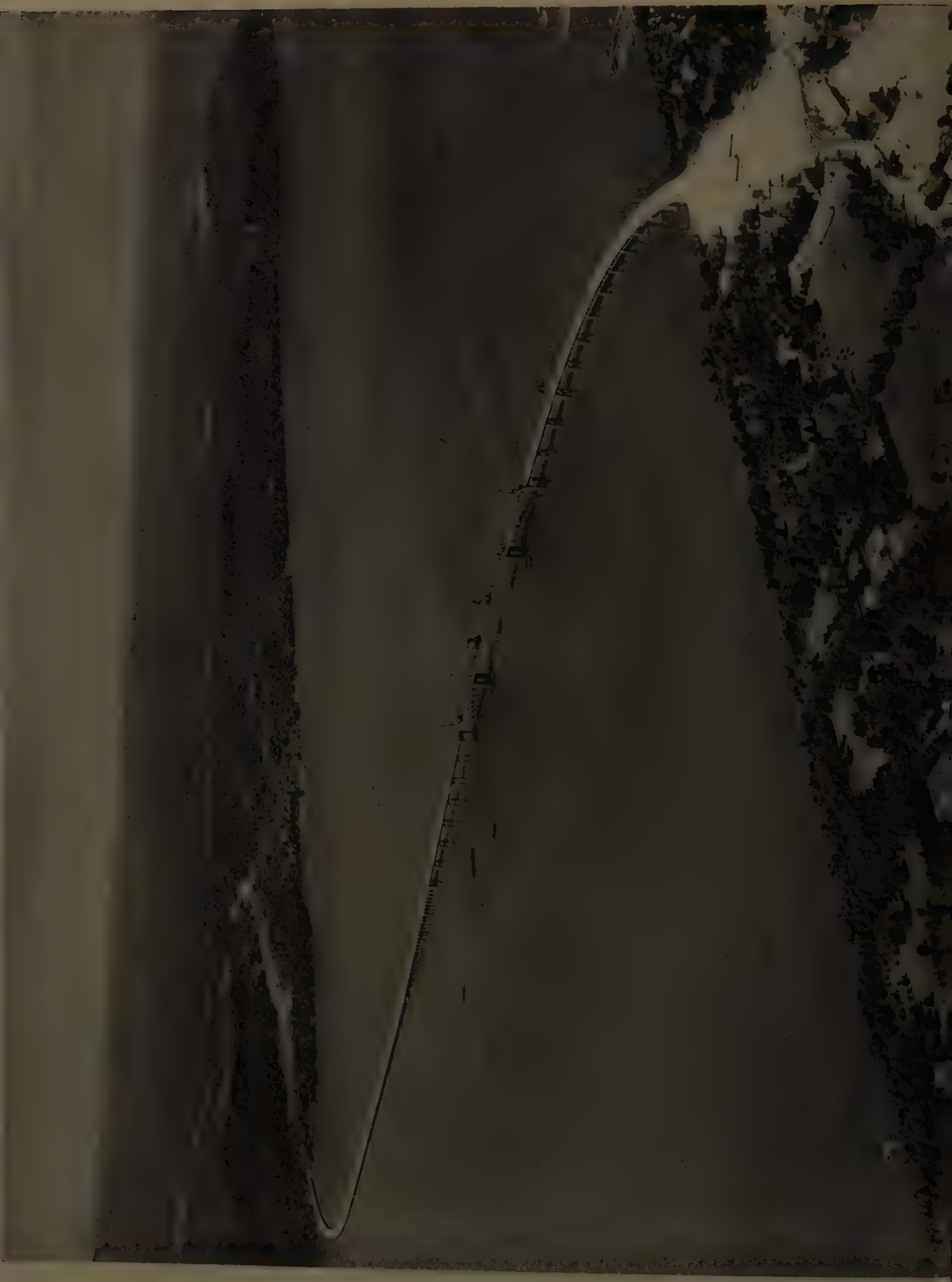

Figure 5.

side of this ravine the base of the diabase is about 40 feet above the river; on the north side it drops down to or below river level, and so continues to the Sparkill.

The sediments exposed on the south side of the ravine, near the wading pool, are closely fractures by several joint sets. Slickensides and striations on some of the joint surfaces that dip steeply to the northwest indicate downward movement on the northwest. Fracture cleavage, in some of the beds, also shows that the northwest side moved down.

A short distance north of the Sparkill the sediments are at about 150 feet in altitude. Apparently, a small graben underlies the northern part of the broad Sparkill Gap, and the creek follows the graben.

At Nyack the structure is somewhat obscure, because of the heavy covering of talus and till. From Sparkill Gap northward the approximate contact of the diabase and the sediments, gradually rising, can be traced halfway to Nyack. At Upper Nyack the contact dips gently to the north. Well logs in Nyack show that the underlying sediments occur up to an altitude of 300 feet. Clearly, there is a broad arch in the structure at Nyack. In view of the fact that the crest of the range here swings a mile westward, down dip, and sharply back again, the rise in structure is greater than that shown on the section.

At the axis of this rising structure is the gap followed by Route 59 and the New York State Thruway (FIGURE 5). The floor and the lower parts of the walls of this gap are covered by loose overburden. It is possible that no faulting occurs here, and that the gap has been excavated along the tension fractures in the crest of the arch. However, if not broken down or flattened, the rising structure toward the gap should expose the sediments in the walls of the gap. Therefore, I have indicated a probable graben at this site.

North of Upper Nyack, where the Palisades swing back close to the river, the Palisades Interstate Park Commission has developed a recreation area on the floor of an old traprock quarry 200 feet above the river. This floor coincides with the contact of the diabase and the sediments. As is true of several other traprock quarries in the Palisades, this quarry was opened up along a fault. Such sites, with the shattered rock and abundant talus in small fragments, were inviting to the quarrymen, for those conditions reduced the need for much drilling and blasting. Just to the north of the quarry the diabase drops down to within 40 feet of the river. The abrupt vertical displacement is about 160 feet.

The exact attitude of this fault is not entirely clear. Some of my observations suggest a normal fault with downthrow on the northwest, while others indicate a reverse fault with upthrow on the southeast. The evidence for the former is more convincing. Apparently, this fault runs southwestward along

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FIGURE 5. From Tarrytown northwestward across the Hudson. Tappan Zee Bridge leads the Thruway to South Nyack and thence through the Nyack gap in the Palisades. North of Upper Nyack, where the ridge swings sharply back to the river, can be seen an old quarry with Rockland Lake over the ridge beyond. At the extreme right, quarry at Rockland Landing. Beyond Rockland Lake the white scar marks the active quarry of the New York Trap Rock Corporation, West Nyack, on the back slope of the ridge between Long Clove and Short Clove. From that point the ridge rises to its culmination in High Tor and then declines as it swings westward to its terminus at Mt. Ivy. In the distance are the Hudson Highlands. Photo by Fairchild Aerial Surveys, Inc., New York, N. Y.

the face of the scarp, beneath the big talus accumulations, and connects with the one in the gap followed by Route 9W.

From the site about a mile north of Upper Nyack northward to the gap at Rockland Lake the base of the sill maintains an altitude above the river of about 40 feet, except at a point about midway where it descends across the bedding to or below the river. At that place the scarp is high and forms a salient into the river. This is in marked contrast to the other sites of offset, where recesses and notches occur, and which I have interpreted as faults.

At the Rockland Lake gap the base of the sill abruptly drops down to or below the river. Till and talus conceal the structure in the floor of the gap, but near the river the diabase outcrop exhibits thin, platy, near-vertical jointing that suggests normal faulting.

In the floor of the gap at Rockland Lake most of the householders are supplied with water from shallow wells in the overburden. However, a deeper well, drilled by the Harriet Drilling Company, New City, N. Y., reached the traprock at 35 feet and, with much difficulty below that, lost the bit at about 100 feet. Difficulty in drilling is common in closely fractured rock, such as that generally found in fault zones.

From the gap at Rockland Lake northward to Trough Hollow, a distance of one-half mile, the sediments are not seen above river level. In this space three traprock quarries have been operated. At the north end of the middle one of these quarries two fault planes, exposed by quarrying, show a strike of N 50 degrees E and dip of 72 degrees to the SE (FIGURE 6). These fault planes show slickensides and are serpentinized. Striations have a steep plunge to the southwest and show that the northeast side moved down. Probably they are subsidiary to the main fault, which lies a short distance to the north, concealed by overburden. At the top of the scarp in the section between these gaps the columns show drag (FIGURE 2), a feature to be expected near the contact (Balk, p. 111). Apparently the top of the scarp here is also the top of the sill. Inasmuch as the top of the scarp here is lower than that to the north and south, where the top of the sill is not shown, this section must be a graben.

From Trough Hollow northward to Long Clove the base of the sill maintains a fairly uniform altitude of about 40 feet. The Red Rock Trail closely follows the contact between the diabase and the sediments.

On the north side of Long Clove the basal contact is exposed in the outcrop along Route 9W at an altitude of 200 feet. Kümmel noted this rise in the base of the sill and attributed it to a discordant contact rather than a fault because, as he says, "seen from the river, the gap at Long Clove did not impress me as being a fault gap" (*op. cit.*, pp. 30, 31).

Actually, the evidence here seems ample to indicate faulting. The gap itself suggests rock weakness; along the river, just south of the gap, is an old traprock quarry, presumably opened where fragmented material was readily available (FIGURE 7); north of the gap the attitude of the sediments differs from that to the south by dipping to the south of west. Outcrops of diabase in the gap have platy, near-vertical fractures, which suggest normal faulting; finally, some of the surfaces in the south wall of the gap are slickensided and striated. Where such features are found at an abrupt offset of the contact between the sediments and the sill, I much prefer the fault interpretation over that of discordance.

Of course, the gap is not a fault gap in the sense that the opening was formed by faulting. Differential weathering and erosion have made the gap on the faulted structure.

Northward from Long Clove the contact declines at an angle of about 10 degrees, so that it dips beneath Route 9W before Short Clove is reached, and descends to an altitude of 150 feet or less. In the Short Clove gap are found steeply dipping, platy joints, some of which are mineralized; others are slickensided. Also, there is a prominent set of diagonal fractures (FIGURE 8). At one point, just south of the Short Clove road, is a zone of gouge about 3 feet wide, with closely fractured rock on both sides. North of the clove, for one quarter of a mile, much of the scarp is covered with thick talus. Beyond, under High Tor, the contact stands at an altitude of about 500 feet. The vertical displacement at Short Clove is at least 350 feet, the largest seen in the Palisades.

FIGURE 6. High-angle subsidiary faults and near-vertical platy joints in the diabase at Trough Hollow. The exposure is about 50 feet high.

Both topography and structure suggest that the total displacement occurred along at least two step faults, rather than a single fracture. The attitudes of fractures and the rock ledges show that these faults have a strike of about N 30 degrees E and dip of 80 degrees SE.

At High Tor the Palisades Ridge leaves the Hudson and swings westward to its terminus at Mt. Ivy. Both Daron and Kümmel thought that this part of the igneous sheet was a dike, cutting diagonally across the sedimentary beds. However, Kümmel states that it is impossible to say whether the contact is that of a continuous dike or whether the trap is concordant in some stretches and cuts across the sediments in a series of steps. Both Darton and Kümmel thought that the contact between the sediments and the diabase stood at about 150 feet at Haverstraw. Just east of Mt. Ivy, though the actual contact is not exposed, the sediments are seen at an altitude of nearly 400 feet. With this picture of the sediments declining westward and the diabase rising westward, it was logical to assume crosscutting.

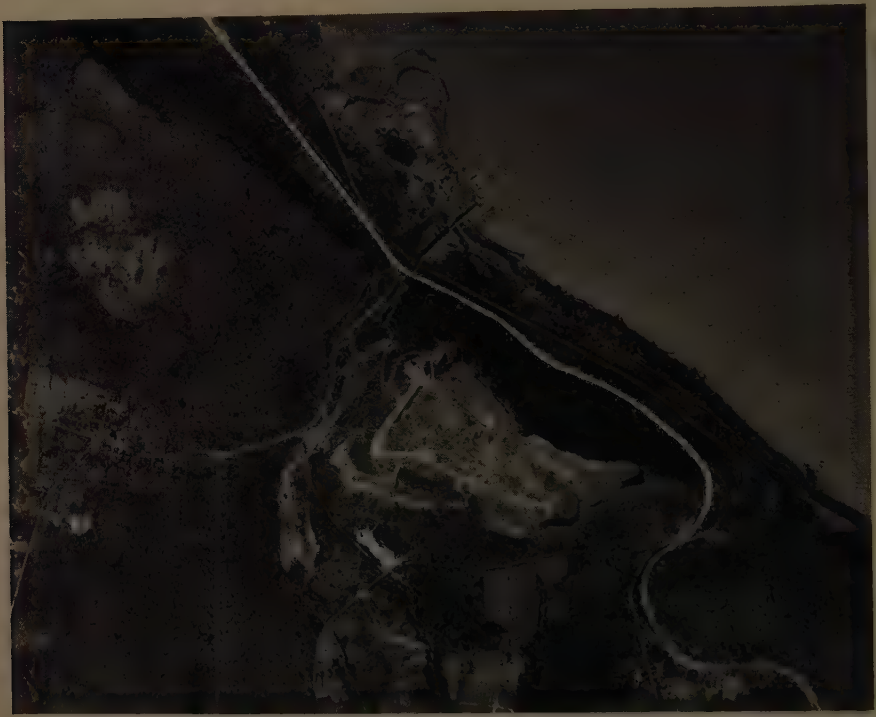

FIGURE 7. Vertical of Long Clove, Short Clove, and vicinity. The prominent white stripe is Route 9W, which goes through Long Clove. Next on the right is the West Shore Railroad, which tunnels through the Palisades 2 miles southeast of Haverstraw. Nearest the river is the Shore Road, which leads to the old quarries on the south side of Long Clove. The big scar between Long and Short Cloves is the active quarry of the New York Trap Rock Corporation. High Tor is in the northwest corner.

My observations, however, including some of outcrops that must have escaped Darton and Kümmel, show that the trap sheet remains a sill all the way.

This different picture is based on the discovery that at Haverstraw the lower contact of the diabase has been upfaulted from the 150-foot position seen by Darton and Kümmel to an altitude of 500 feet. Perhaps it would be more accurate to say that the outcrops which they saw have been downfaulted from an altitude of 500 feet to one of 150 feet. From the 500-foot level the contact declines gently westward in conformity with the sediments as shown by the following observations.

On the trail from Route 9W to High Tor, north of the big talus slope north of Short Clove, there is a bench about 60 feet wide at an altitude of 500 feet. In the scrap of this bench, 100 yards south of the trail, is an outcrop of baked sediments, apparently near the contact with the sill. One hundred yards north of the trail is seen a ledge of fine grained, silicified trap, apparently near the contact with the sediments. This narrow bench is probably the result of differential weathering along the olivine zone a few feet above the contact.

Figure 8. Diagonal shear fractures in diabase along Route 9W at Short Clove. The view is just south of the axis of the Clove and looking west.

Beneath Little Tor the sediments crop out in an abandoned brownstone quarry at an altitude of about 450 feet. About one mile to the west, just below the Central Highway gap, is another small outcrop of the sediments, not seen by Darton and Kümmel, which stands at an altitude of about 420 feet. Two miles farther west, near Mt. Ivy, the sediments stand at a little less than 400 feet.

Thus, the igneous sheet declines westward with the sediments, instead of rising across them. At each site where the sediments crop out on the scarp slope they appear to be concordant with the overlying igneous sheet; that is, the columnar joints in the diabase are perpendicular to the bedding of the sediments.

In this western swing of the Palisades the dip of the sediments, some 10 degrees or less, changes from southwest at Haverstraw to almost due south just east of Mt. Ivy. Thus, the average westward component of the dip is very small, probably not more than half a degree. There are possible small normal faults east and west of Little Tor and at the Central Highway gap. Kümmel apologized because his instrument could not measure angles closer than one degree. I should be happy indeed if I could be sure that my measurements were within one degree, not because of any limitation of the clinometer, but because of the small outcrops and irregular surfaces of the bedding planes.

Western Termination of the Ridge

At Mt. Ivy the ridge terminates by sloping down from an altitude of 750 feet to the general level of the country at about 400 feet, and the traprock disappears beneath a covering of glacial overburden. Although the dip of the enclosing sediments becomes westerly in this vicinity, the slope of the end of the ridge is substantially greater than the westward inclination of the rocks. A contributing cause for the termination of the ridge at this place appears to be that of downfaulting on the west. In the road cut of the Interstate Parkway the diabase is shattered and slickensided, and the columnar joints are well obscured by other fractures. That the base of the diabase did not here rise to the surface is attested by a recent well at the home of T. J. Connor, just west of Route 45. The bottom of this well, 100 feet below the surface, is still in the diabase. Another suggestion of faulting at Mt. Ivy is a traprock quarry located where the diabase is already fragmented to a size for easy handling.

The present rather gradual slope at the termination of the range does not reflect the angle of the fault here. Perhaps the fault has a high angle, but subsequent weathering and mass movement have subdued the slope. In addition, the Pleistocene ice, moving southward through this lowland, also modified the structural slope by abrading it and by leaving a mantle of till and outwash in the lowland.

Relation of Gaps to Cross Faults

By now it is evident, if faulting is accepted, that the main gaps in the range are located at cross faults. Both Darton and Kümmel noted the coincidence of the gaps with offsets of the base of the trap. Although they suggested the possibility of faulting at certain sites, they preferred to explain most of the offsets by stratigraphic migration rather than by faulting.

Kümmel, however (p. 45), was reasonably certain of a diagonal fault at Sparkill. He also indicated the probability of a small fault at Trough Hollow, but said that the phenomena observed there "may be due solely to a change in horizon of the trap." In connection with other gaps he says (p. 45): "Some observers have seen evidence of faulting in the gaps at Long Clove and Short Clove, but, after careful examination of the ground, I was not convinced that they mark fault lines. Manifestly the gaps themselves do not necessarily indicate faulting. As already suggested, these gaps with several others of accordant height are probably parts of a drainage system formed when the land stood somewhat lower with respect to sea level than at present. Their location may have been determined by faults, but I could find no positive evidence that such was the case. All the facts observed can be accounted for without calling in the aid of faulting."

Without any mention of the structure, Johnson (1931) classified the broad Sparkill gap as the former water gap of a large superposed stream, the Hudson, and, by inference, the smaller gaps as the former water gaps of smaller superposed streams, all later diverted by piracy.

Apparently, in the views of Darton and Kümmel, it is a fortuitous circumstance that the gaps are located where offsets of the diabase occur. Darton and Kümmel do not explain why the migration of the magma across the beds would cause a zone of weakness.

In Johnson's view, also, although he does not mention local structures, it is fortuitous that streams were superposed across the diabase where its base has marked offsets. It may be that the Hudson formerly flowed through the Sparkill gap, but that is not necessary to explain the gap. Before glaciation this gap had an irregular floor; ravines with jagged divides had been etched out along the faults. This could have been accomplished by local drainage. Glaciation scoured off the projections and filled the ravines, leaving a fairly flat floor about two miles wide.

Regarding the origin of topographic gaps—water gaps and the so-called wind gaps—in hard rock beds there is strong difference of opinion. On the one hand are those who believe that a notch, or gap, of any considerable size (depth) in a hard rock ridge must necessarily have been made by a stream flowing across the hard rock. Apparently they think that perennial running water is necessary to corrode and remove the material and that, if a stream is now flowing through the gap, that stream, starting at the top or above (superposed), has carved the gap. If no stream now flows through the gap, the one that did the cutting, according to this school of thought, must have been stolen by another that is more favorably situated.

On the other hand are those, of whom I am one, who believe that gaps may be made without through-flowing streams, although it is not denied that some dry gaps have had such streams that were later captured.

In addition to stream action there are other important processes involved in the formation and removal of debris. Along a zone of close fracturing the processes of chemical weathering can work more deeply than usual; frost heaving and the wedge-work of ice are especially effective. Once the material is decomposed or disintegrated, it moves down slope by sheetwash, by frost action, by slumping, by creep, by rillwash, by mud flows, and even by landslides.

After a small depression is formed by the above processes, water from both sides drains into it. The wet-weather rills carry away the weathered material and the depression is enlarged to a col. As the col grows deeper and wider, stream action becomes greater, for more water is gathered to feed the rills and they are better able to remove the debris. As long as the floor of the col remains above the level of the drainage on both sides of the ridge of hard rock, drainage from the gap will flow both ways, and we have a so-called wind gap. If the drainage levels on the two sides of the ridge are substantially different, the lowering of the gap floor below the level of the higher drainage will bring the water one way through the notch, producing a water gap.

If we define a wind gap as a notch without a through-flowing stream, most of the gaps in the Palisades are wind gaps. It is probable that a stream formerly flowed to the Hudson through the gap at Rockland Lake, draining a considerable area behind the ridge. If so, that stream now is blocked by glacial fill in the gap, and the drainage goes to the Hackensack River. At Piermont the Sparkill cuts through the ridge, draining a substantial area to the Hudson. Its pattern west of the ridge suggests capture of one or more former tributaries to the Hackensack.

Upper Contact of the Diabase and Sediments

Along the back slope of the Palisades the undisturbed contact of the sedimentary beds overlying the diabase can be seen at only a few places. Glacial till or other surficial deposits mostly conceal the contact. At some places, for example, just south of Nyack and also just north of Nyack, near Valley Cottage, the slope is relatively gentle, about equal to the dip of the sill. There one can see the fine-grained top of the sill with patches of baked shale adhering to it. At such sites there is no suggestion of discordance or of faulting. At other localities the back slope of the ridge is much steeper than the dip of the structure.

About two miles southeast of Haverstraw the West Shore branch of the New York Central Railroad (FIGURE 7) tunnels through the Palisades. At the south portal of this tunnel the excavation exposes the upper contact of the diabase with the sediments. The strike of this contact is N 60 degrees W and the dip is 60 degrees SW. Both Darton and Kümmel have published illustrations of this contact; both interpret it as a feeder dike cutting across the sediments at a fairly high angle.

After interpreting this as a dike contact, both Darton and Kümmel extend the same interpretation to all portions of the western slope of the Palisades where the surface slope is greater than the dip of the rocks. Both cite the entrance to the railroad tunnel west of Weehawken, N. J., as another example of the dike contact with the sediments. At each place the evidence of a fault contact, in my opinion, far outweighs that of a cross-cutting dike.

FIGURES 9 and 10 illustrate the conditions at the south portal of the railroad tunnel southeast of Haverstraw. A ravine filled with glacial till at the top and with talus below coincides with the contact of the diabase and the sedimentaries. Obviously, there has been rapid weathering along the contact. If this were an intrusive contact the sedimentaries would have been baked and hardened and would not be a zone of rapid weathering.

On both sides of the contact the rocks are closely fractured. The most prominent joints in the sedimentaries dip to the northeast at about 75 degrees. They are here interpreted as feather joints associated with the fault that dips southwest at 60 degrees. In the diabase there are 4 main sets of fractures. The columnar set (or system) is somewhat obscured near the contact, but is more evident farther away. The columns are tilted gently to the southwest in conformity with the dip of the sediments. There is the usual set of nearly horizontal joints perpendicular to the columnar ones. In addition to these joint sets, typical of the undisturbed diabase everywhere, there is a set of closely spaced platy joints, parallel to the contact. These are the most prominent joints in the contact zone, and they should be labeled as shear fractures or as subsidiary faults. A fourth set of joints, which may be designated as antithetic faults, runs nearly perpendicular to the fault plane and extends only a short distance from it.

In the wall on the west side of the tracks adjacent to the main fault are two wedge-shaped forms of fine-grained trap. They are closely fractured by joints parallel to the contact plane. Both Darton and Kümmel represented these forms as apophyses of a dike. I think that it is much more accurate to designate them as horses associated with a normal fault.

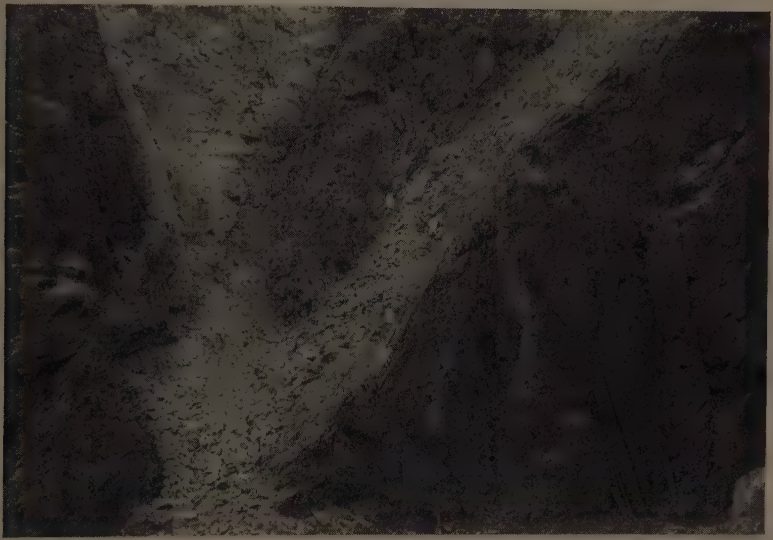

FIGURE 9. West wall of the south portal of the West Shore Railroad tunnel 2 miles south of Haverstraw. The fault plane dips steeply to the left (S-SW). Horses of diabase are seen to the left of the main fault plane. Farther left are the sediments; diabase is to the right.

Although weathering has destroyed the original contact surfaces, some of the fragments in the talus show slickensides. Lower in the cut the traprock is seen on both sides of the fault. On the east side of the tracks the concordant contact of the trap and the overlying beds can be traced for 100 feet, until the southwestward dip carries it beneath the roadway. Thus, the evidence for faulting is ample.

The magnitude of the vertical displacement along this fault can be stated only as a minimum. It is about 60 feet from the top of the diabase in the hanging wall to the eroded surface of the diabase in the foot wall. The displacement, then, is 60 feet plus the amount of erosion on the footwall since faulting.

In the southwest part of the New York Trap Rock Corporation quarry between Long Clove and Short Clove the joint pattern suggests faulting on the southwest side of the ridge. There the columnar joints, though still faintly visible in their usual altitude, are obscured by other more prominent sets.

On the south side of the ridge west of Short Clove, along and near South Mountain Road, are two other localities that show the fault nature of the upper contact. On the south shore of Lake Lucille, 3 miles west of the railroad tunnel, well-exposed sediments dip northward, toward the ridge, at an angle of about 10 degrees. A few hundred yards to the north, north of South Mountain Road, the apparent top of the diabase is exposed, dipping southward. Although the contact is not exposed here, faulting is clearly indicated by the dip of the overlying beds toward the underlying rock.

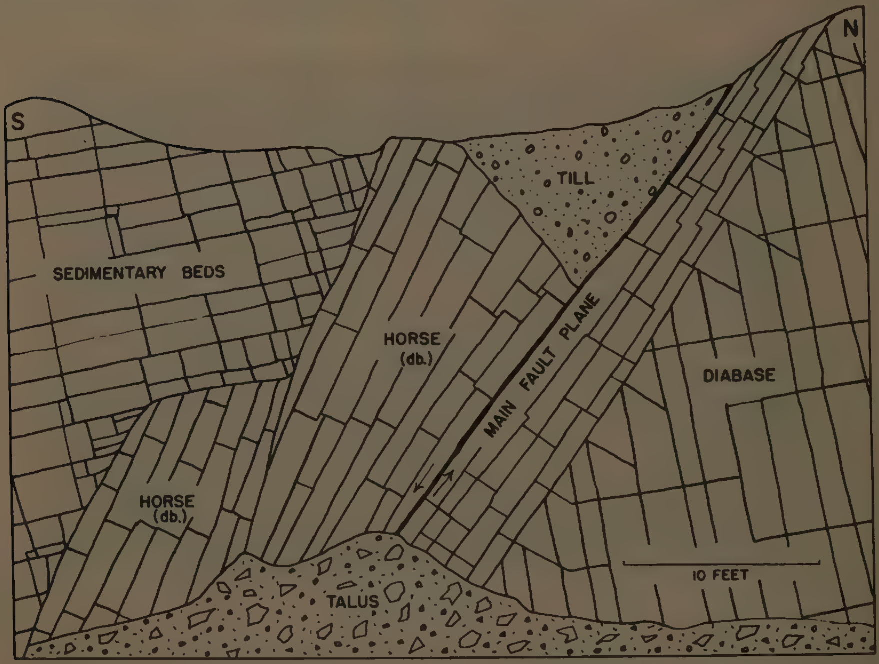

FIGURE 10. Field sketch of the features shown in FIGURE 9.

About two and one-half miles farther west, where a little brook comes down near the end of the ridge, the sediments are exposed both north and south of South Mountain Road. At this site, also, the beds dip gently northward toward the ridge. On the north side of the ridge opposite this locality, the underlying sediments dip southward at about 10 degrees. Faulting on the south side of the ridge seems the best explanation.

The upper contact of the intrusive appears at a few sites near the foot of the ridge north of South Mountain Road (the east-west road south of the ridge) and north of the fault line. The best exposures are in the excavation for the dwelling of Will Burtin and in the ravine a few yards to the west. At these sites the contact is somewhat irregular, the diabase jutting up into the sediments in small dikes, stringers, cupolas, and other irregularities.

At other sites along the back foot of the range, where the slope is exceptionally steep and the contact or near-contact can not be seen, I have indicated probable faults on the map (FIGURE 1). However, it is possible that some of these oversteepened slopes may be due to ice erosion.

In the lowland south of the westward-trending Palisades ridge (South Mountain) the small ridges have a northward trend. This discrepancy in trends has been cited as evidence that the trap sheet in the main ridge is a dike. Faulting along the south side of South Mountain could produce the same discrepancy and is a more probable explanation.

It is not clear whether the trend of the small ridges in the lowland coincides with the strike of the sedimentary beds, for the ridges consist mostly of till. Cuts of the Thruway, one estimated to be 75 feet deep, do not expose bedrock for a distance of 5 miles west of West Nyack.

Thickness of the Sill

At several places along the river front the approximate altitude and dip of the base of the sill can be measured. On the back slope of the ridge, however, the top of the sill can be seen at fewer sites. Where the base and the top are observed opposite each other down the dip, and without an intervening fault, the thickness of the sill can be calculated readily. The results of a few of these calculations are given below.

In Sparkill gap the top of the sill is exposed at an altitude of 65 feet (bench mark) at the intersection of Oak Tree and Carteret roads. Up dip at the river front, one and one-sixteenth miles away, the base is at about 30 feet. Calculation indicates a thickness of about 900 feet. Along Route 303, two tenths of a mile south of Route 59, the top of the sill is at 100 feet. On the scarp slope opposite, 1 mile distant, the base, though not seen, is believed to be at about 300 feet. Here the thickness is about 750 feet. Beneath Little Tor the base is at about 450 feet, and the opposite top near South Mountain Road is at 150 feet, indicating a thickness here of about 600 feet. Near the western end of the ridge east of Mt. Ivy, the thickness appears to be about 400 feet.

Darton's statement (p. 44) that ". . . there is not less than 850 feet of trap in the escarpment at High Torne" is based mainly on the false assumption that the base of the sill there coincides with the base of the scarp. Actually, the base of the sill there, is about 350 feet higher than Darton presumed it to be. As a minor factor, it may be noted that the maps of Darton's time show the High Tor as being somewhat higher than do the recent maps.

If these observations are essentially correct, and no substantial faults intervene to nullify the calculations, the thickness of the sill gradually decreases northward and westward.

Effects of Glaciation

Some of the effects of glaciation were observed and recorded. The direction of glacial striae are shown on the map (FIGURE 1). In addition to their local implications, they may be of value in mapping the regional movement of the ice.

On the uplands the striae show a fairly constant southward trend in the north, veering to the southeast in the south, that is, fanning out from the great Hackensack Lowland lobe. In the gaps of the ridge the striae often depart from the general trend and follow the axes of the gaps. In the Hudson trench no striae were seen on the west side of the river, but those on the east side (not shown on the map) show that the ice followed the river channel regardless of the general direction of motion on the uplands.

The effects of glaciation on the topography of the Palisades ridge, though probably not striking, were of some importance. Along the river front the ice no doubt smoothed off projecting spurs and carried away most of the talus, so that the present accumulation there is largely postglacial. At the western end of the range there is evidence of strong abrasion by the ice as it was deflected westward around this projection. Just south of Little Tor, in the lee of the ridge where the ice moved directly across it, a little tarn nestles in an apparent ice-plucked basin.

No doubt, the gaps were somewhat modified by erosion when the ice moved through them. More or less till was left on the gap floors when the ice melted. As has been mentioned, the till filling at Rockland Lake gap possibly has blocked a former small tributary to the Hudson. At Nyack, the entire terraced slope on which the city is built is well covered with till. In the broad floor of Sparkill gap the bedrock is concealed nearly everywhere by a covering of till.

South of Sparkill gap the smooth crestline of the range is in part the result of ice erosion, for there the ice moved diagonally across the Palisades and would tend to rasp off small projections.

Nearly everywhere the west foot of the range is covered with a blanket of glacial deposits. This covering is the great obstacle to direct observations of the upper contact between the diabase and the overlying sedimentary beds.

CONCLUSIONS

My observations and opinions on the structural relations of the diabase with its enclosing sediments and on the origin of the gaps through the ridge are as follows:

The base of the sill is in general concordant with the sediments, and its abrupt vertical offsets are due to faults rather than to stratigraphic migration.

With a change in direction of dip from west to south, the westward swing of the diabase from Haverstraw to Mt. Ivy continues as a sill, rather than as a dike that rises gradually, or intermittently, across the structure.

Where the upper contact of the diabase and the sediments on the back slope of the Palisades is not concordant, the contact is that of a normal fault rather than that of a feeder dike.

The notches, or gaps, in the ridge have been etched out by weathering, mass wasting, and rill erosion along zones weakened by faulting, rather than by the corrasion of fortuitously superposed, through-flowing, streams.

It is well to close with a quotation from Davis' paper on "The Triassic Formation of Connecticut" (p. 137): "Most of the faults shown on the map . . . are not known by direct observation. They can therefore be assured only when the inference is legitimate and the argument logical . . . . Over the formation as a whole, if the drift were stripped off and the rocks laid bare, the faulting would probably be found much more extensive and intricate than it is represented on the map . . ."

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Discussion of the Paper

George F. Adams (*The City College, New York, N. Y.*): H. D. Thompson has explained Sparkill Gap as a relatively low area developed by differential erosion of a grabenlike structure. It is not clear how this effect is accomplished. The effect of cross-faulting in a dipping layer of unlimited extent with respect to the present erosion level is simply to shift the position of the layer and the locus of the ridge line produced by differential erosion of the weak beds on either side. This seems to be precisely the case at Long Clove. No breakdown in the ridge line at Sparkill Gap should be expected on these grounds even if the faults postulated are accepted. Instead, the ridge line with the same dissected appearance as occurs farther north should be slightly offset near the fault lines at the site of Sparkill Gap. The only possible way of producing Sparkill Gap by faulting as pictured by Thompson would be to have cross-faults and crushed zones spaced every few yards so that the entire sill in this region would be a rock of medium resistance to erosion. This does not appear to be the case.

Thompson states that if the gap is produced by faulting and differential erosion there is no need to invoke a through-flowing stream to explain it. Even if we accept the faults postulated, this does not throw out forever the probability of a through-flowing stream, because such a stream could hardly have avoided all the faults postulated. Inasmuch as the theory of a superposed subsequent, as conceived by Douglas Johnson, depends on a whole assemblage of features, it must not be discarded on the basis of one feature, Sparkill Gap, when the alternate explanation of its origin may itself be questioned on reasonable grounds.

The striking topographic contrasts north and south of the gap are attributed by Thompson to differences in fault spacing. South of the gap the broad even surface of the Palisades is attributed to the occurrence of widely spaced faults. North of the gap, the more rounded hills are attributed to closely spaced faults. I do not have the cross sections exhibited by Thompson, but I recall that for several miles north of the gap the area is fault-free. If this area is compared to an area of similar length south of the gap, according to Thompson's general explanation, the two areas should have similar topographic expression. The fact that they are strikingly different seems to require a different explanation. The topographic contrasts are precisely those called for by the theory of the superposed subsequent.

I accordingly conclude that Thompson has in no way invalidated either the general theory of regional superposition or its application in this region.

H. D. THOMPSON (*Hunter College, New York, N. Y.*): George F. Adams defends Douglas Johnson's hypothesis of regional superposition of Appalachian drainage from a coastal plain cover. That hypothesis was eloquently stated by Johnson in 1931. At first the hypothesis was widely accepted; since then it has lost favor. One objection to it is the fact that no inland remnants of the coastal plain cover have been found. A stronger objection is provided by the demonstration that many of the water gaps and wind gaps in the hard rock ridges are at sites of relative weakness, a circumstance that would be highly improbable in the case of random superposition.

At Sparkill Gap several transverse faults cut the Palisades Ridge. These faults provide a broad belt of relative weakness in the ridge and, therefore, mark the site of a broad gap. It may be that the Hudson River formerly followed a course through the gap and played a major role in its excavation, but hardly as a superposed stream. If the gap were located a little to the north or a little to the south, where faulting is not evident, the case for superposition would be much stronger.

STRUCTURE OF THE PALISADES INTRUSION AT HAVERSTRAW AND WEST NYACK, N. Y.

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Introduction

The Palisades intrusion exposed along the west shore of the Hudson River in New Jersey has been interpreted on good evidence as a sill that intruded terrestrial clastics (Newark Group) of Late Triassic age. However, I have long been dissatisfied with the concept of the sill's extension beneath the Triassic basin to the border faults along the margins of the crystalline Highlands of New Jersey (and New York). This interpretation was the basis of Lobeck's diagrams (1928, 1932, 1952), which have appeared in numerous texts and reference books (for example King, 1951) without change or critical comment.

At this writing, new evidence opposed to this contention has become available in the New Jersey portion of the Palisades intrusion. Recent enlargement of the Ward Trucking Company's parking lot in North Bergen, N. J. exposed the upper contact of the Palisades dipping 65° westward and cross-cutting gently dipping Triassic sandstones.

My work in the northward extension of the Palisades in New York State is believed to shed some light on the structural behavior of the "sill" which might give impetus to a re-examination of the longheld structural concepts concerning the New Jersey portion of the intrusion.

Previous Work

The present study is based on data obtained from the operation of the Haverstraw and West Nyack trap rock quarries (FIGURE 1) in my capacity as geological consultant for the New York Trap Rock Corporation, West Nyack, N. Y.

Previous published work in this region is limited to studies by Darton (1890) and Kümmel (1900) as discussed in some detail by Thompson elsewhere in this publication. The findings of these writers may be summarized as follows:

(1) Vertical offsets at the base of the sill (along the shores of the Hudson River) are the result of "lateral migration" across sedimentary beds.

(2) Portions of the backslope of the Palisades ridge which have a topographic slope steeper than the dip of the sediments are developed on steeply dipping "feeder" dikes.

(3) The westward curving terminus of the exposed Palisades ridge between Haverstraw and Mt. Ivy (FIGURE 1) is a dike cutting across the bedding of the sediments at a low angle (Darton) or in abrupt steps (Kümmel).

(4) Gaps in the ridge represent former stream courses. The possible existence of cross faults at some gaps is mentioned, but their presence is considered speculative owing to the lack of concrete evidence.

At present, some magnetometer and seismic refraction studies in the Haverstraw to Mt. Ivy portion of the Palisades are being undertaken by several investigators. Results of these studies, however, are not as yet available.

Preliminary findings leading to the presentation of this paper were published by myself at an earlier date (Lowe, 1958).

Regional Geomorphology

The Palisades north of Nyack, N. Y. form a prominent curving ridge that is sickle-shaped in plan-view (FIGURE 1). Its serrated crest rises to a maximum elevation of 832 ft. above sea level at High Tor, south of Haverstraw (FIGURES

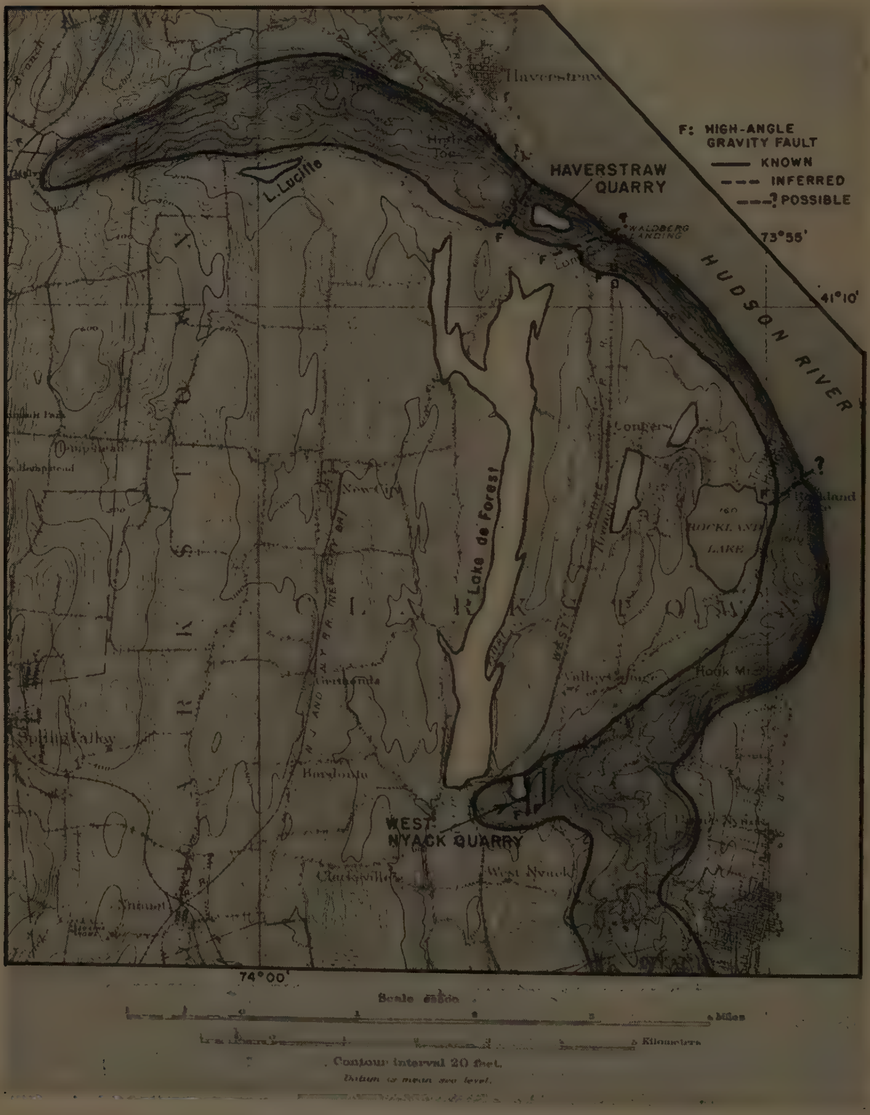

FIGURE 1. The Palisades from Nyack to Haverstraw, N. Y.

1 and 3). The ridge is asymmetrical in cross section, with a precipitous escarpment along its outer, convex side and a gentler slope (backslope) along its inner, concave margin. It should be noted that portions of the backslope are considerably steeper than the backslope of the Palisades in New Jersey about 10 miles to the south.

Topographic expression of the ridge alone strongly suggests that it was developed on a sheetlike intrusion of diabase having roughly the shape of a half saucer.

Clarkstown township, located largely within the "sickle," is underlain by red sandstones and shales of Late Triassic age mantled in places by glacial deposits rarely exceeding 30 feet in thickness. The NS strike and gentle (5° to 15°) westerly dip of the Triassic bedrock is unmistakably reflected in the geomorphology of the region. Ridges and valleys are principally developed in the NS direction. The remarkable linearity of the major stream courses is illustrated by Lake de Forest, formed by impounding the headwaters of the Hackensack River (FIGURE 1). Ridges in the vicinity of New City and Spring Valley are small cuestas with relatively steeper eastern slopes and very gentle west slopes. These features, though recognizable on the old mile-to-the-inch base map used for FIGURE 1, are greatly emphasized on the recent 1:24,000 maps having a contour interval of 10 feet.

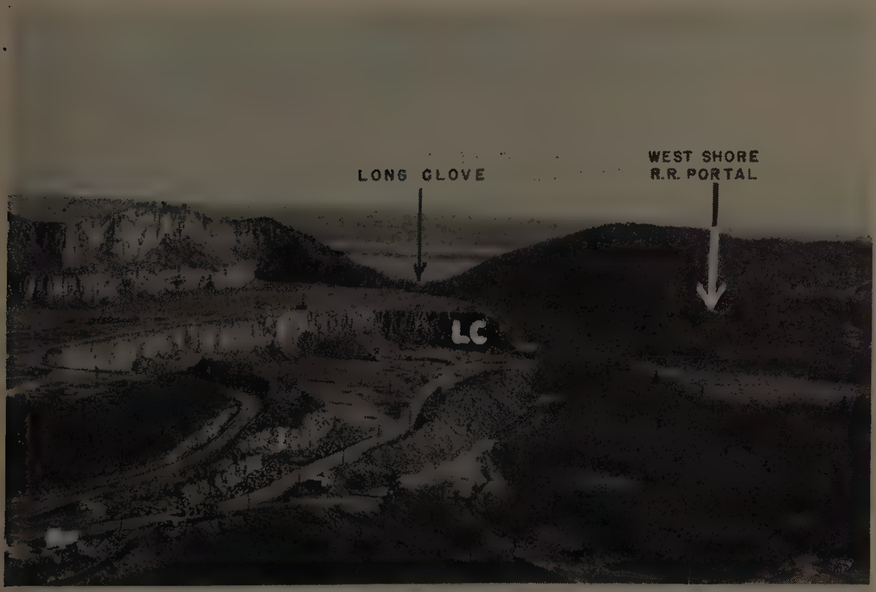

FIGURE 2. Haverstraw quarry; view to the southeast. LC indicates the leaning columns shown in detail in FIGURE 7.

The divergence between the ridge trend in the lowland and the trend of the Palisades ridge is particularly noticeable along the inner margin of the intrusion between Long Clove and Mt. Ivy (FIGURE 1). There a nearly right-angle

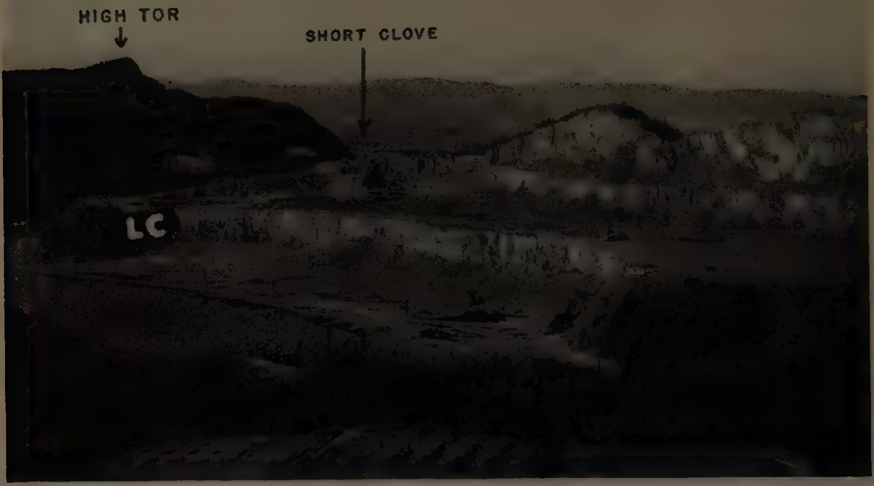

Figure 3. Haverstraw quarry; view to the northeast. LC indicates the leaning columns.

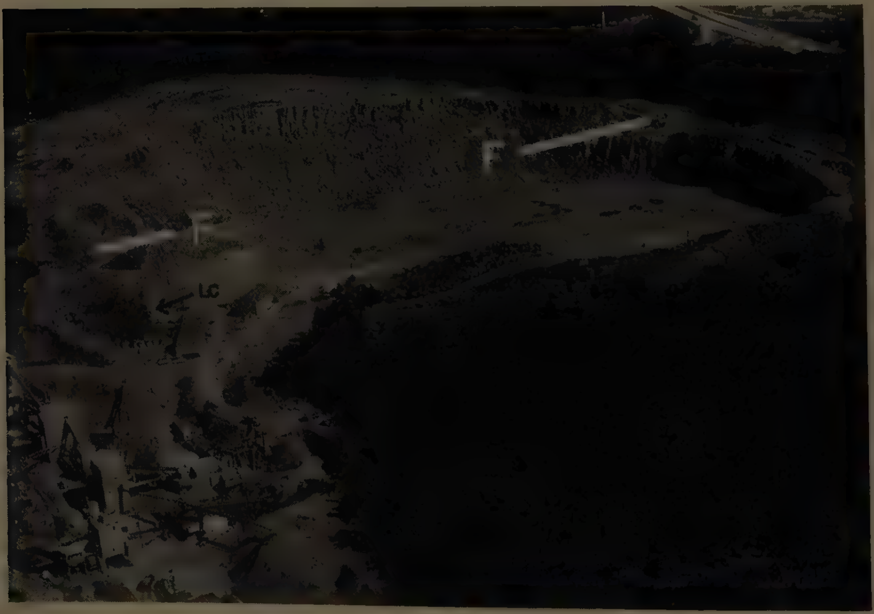

Figure 4. West Nyack quarry; view to the southeast. LC indicates leaning columns; F, a normal fault.

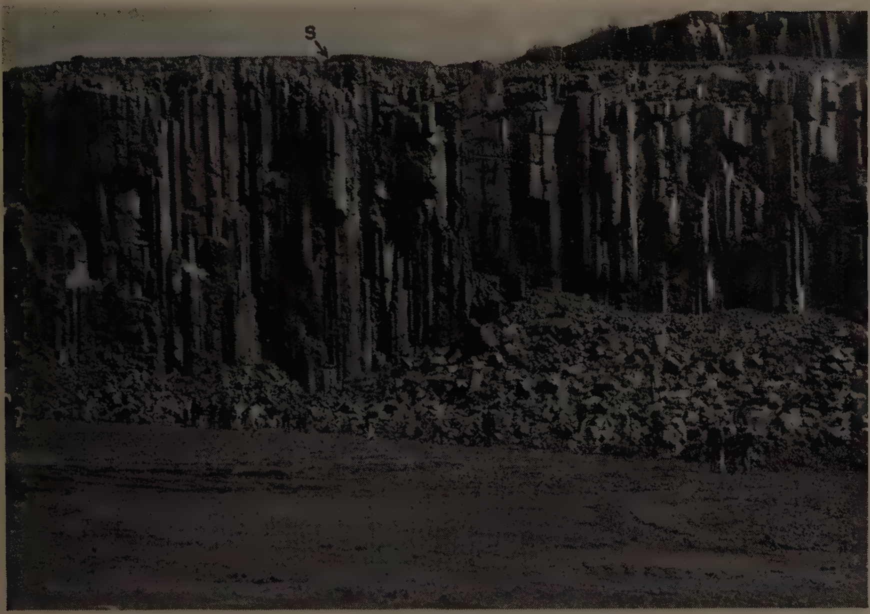

FIGURE 5. Lower level of the Haverstraw quarry; view to the east. S indicates fracture zone.

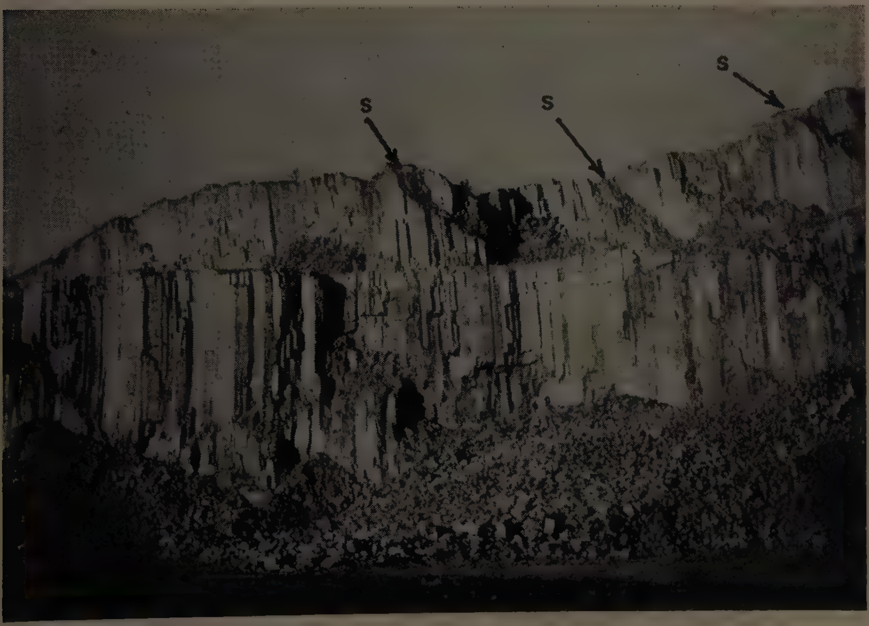

FIGURE 6. Upper and lower levels of the Haverstraw quarry; view to the northeast. S indicates shear fractures.

relationship exists, making the dike structure of the intrusion a virtual certainty.

At the Haverstraw quarry one such NS trending ridge abutting against the diabase intrusion was core-drilled and found to be underlain by Triassic red-beds dipping 20° westward (D.20 of Section *B–B′*, FIGURE 8).

Under the circumstances, it is difficult to accept Thompson's thesis that the Palisades intrusion west of Haverstraw is a sill. It is undoubtedly true that topographic expression cannot always be relied upon as proof of geologic structure, but it appears also certain that a structural hypothesis may not ignore clear-cut geomorphic evidence.

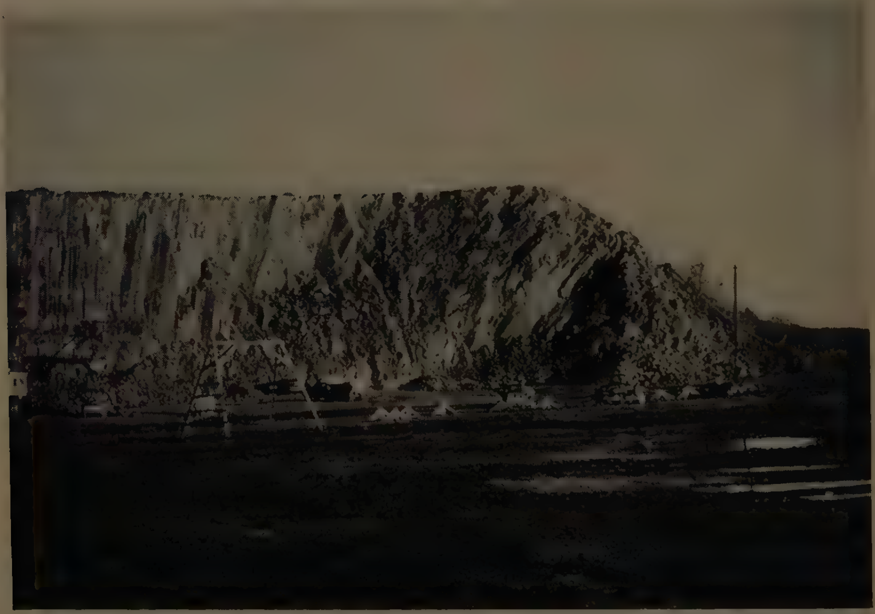

FIGURE 7. Lower level of the Haverstraw quarry; view to the southeast. Leaning columns of FIGURE 2 are shown close at hand.

I agree with the concept of Darton and Kümmel that the Palisades north of Nyack is a cross-cutting, dikelike sheet. The principal point at issue, then, is the exact structural attitude of this sheet.

Geologic Structures

Primary fractures. The columnar structure of the Palisades intrusion produced by tensional cooling joints, arranged in polygonal and, less commonly, cylindrical patterns, is the most striking structural feature exposed along the escarpment facing the Hudson River and in the walls of the trap rock quarries (FIGURES 2 to 7). These columns are explained as having developed perpendicular to isothermal surfaces during cooling (Bucher and Kerr, 1948, p. 111). In sheet intrusions such as the Palisades, such isothermal surfaces are generally

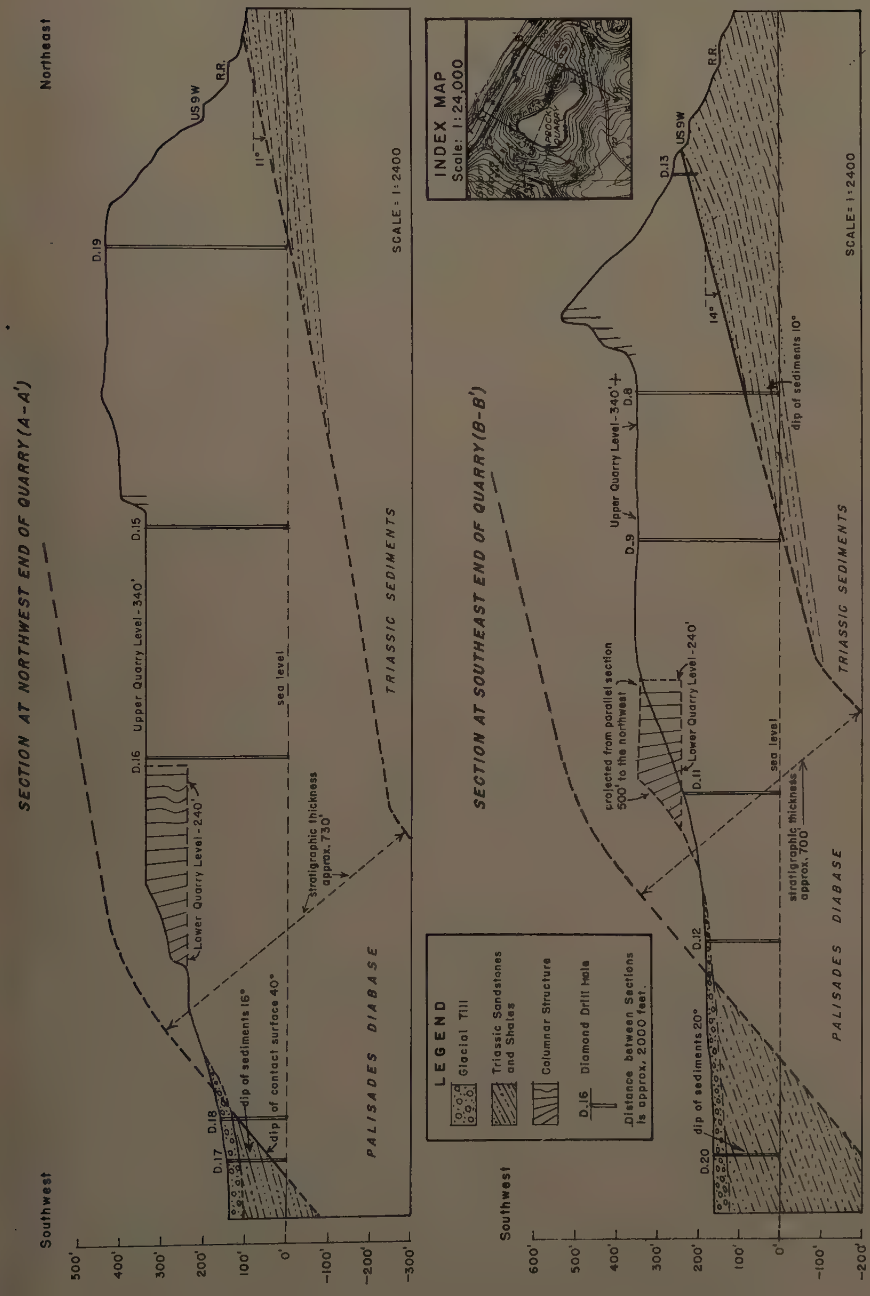

FIGURE 8. Cross sections of Haverstraw quarry.

more or less parallel to the contact surfaces, so that the resulting columns stand essentially perpendicular to the contacts. This fact has been observed in numerous lava flows and tabular intrusions the world over.

Throughout the length of the Palisades ridge from Staten Island to Haverstraw the columnar structure is vertical or dips steeply (70° to 85°) to the east or northeast. This attitude reflects the gentle westerly dip of the intrusive sheet, a feature which it retains in the region under discussion (FIGURES 5 and 6).

Removal of rock from the lower level of the Haverstraw quarry exposed two walls (LC of FIGURES 2 and 3) intersecting the backslope of the ridge and extending roughly perpendicular to the strike of the intrusive sheet. In both exposures the attitude of the columns changes gradually from vertical to approximately 45° NE in the down-dip (SW) direction (FIGURE 7). The term "leaning columns" is used to describe this feature. A similar observation was made at the entrance to the West Nyack quarry (FIGURE 1 and LC of FIGURE 4), except that the dip of the leaning columns is to the south.

These observations gave the first clue of a change in the dip of the trap sheet from about 15° to 45° along the backslope of the ridge.

The northwest wall of the lower level (LC of FIGURE 3) also exhibits several "bent" columns, shown diagrammatically in Section *A–A′* of FIGURE 8. These are interpreted as the result of "hot spots" that developed in the crystallizing magma, causing "bulging" of the isothermal surfaces. Bucher and Kerr (1948, p. 112) use the same concept to explain the curvicolumnar structure in the basalt flows of the First Watchung Range of New Jersey.

It has been suggested by some that the bending of the columns might have resulted from movement of the nearly solid but still somewhat mobile rock mass. This contention must be rejected on the grounds that tension fractures of this type form upon complete solidification, and any subsequent movement would tend to fracture and displace the columns rather than produce smooth curved surfaces. This mechanism might be applicable to deformation in the plastic state, which certainly did not exist at the relatively shallow depth of the Palisades intrusion.

The columnar structure is cut at irregular intervals by joints oriented roughly parallel to the contact surfaces of the intrusive sheet (FIGURES 5 and 6). These are the very fractures that are so prominently developed (at the expense of the columnar structure) within 10 to 20 feet of the lower contact at Edgewater, N. J. In the Haverstraw quarry, their parallelism to the contact surfaces (inferred in part) and consequent high-angle relationship to the columnar structure appear to be maintained even where the columns are seen to "lean" (FIGURE 7).

Another persistent although widely spaced set of joints cuts obliquely across the columns. In the Haverstraw quarry such joints strike approximately EW and dip from 40° to 60° S. They are characteristically filled with chlorite and occasionally with zeolites, carbonates, and quartz, probably of late magmatic origin. They, too, are interpreted as primary fractures, even though later shearing movements (Palisades disturbance?) utilized them and produced slickensiding and displacements measured in inches rather than feet (*S* of FIG-

URES 5 and 6). It must be borne in mind that prominent slickensides on chlorite-coated surfaces can be formed by movements of fractions of an inch and are no proof of large-scale displacement.

Thompson's claim that such fractures usually accompany normal or reverse faults and tend to obscure the columnar jointing is not substantiated by their excellent exposures in the Haverstraw quarry (*S* of FIGURE 6).

Tectonic fractures. High-angle longitudinal and cross faults cut the Palisades intrusion, but are probably less numerous and less extensive than suggested by Thompson. In this region of broad surficial cover, conclusive evidence of major faulting is rarely exposed, as indicated by Darton and Kümmel about 60 years ago. Indirect evidence such as slickensiding, close spacing of joints, feather joints must be used with considerable circumspection.

Careful study of faults exposed in the quarries reveals the following:

(1) Brecciation (and gouge) zones rarely exceed widths of 10 to 15 feet (*F* of FIGURE 4).

(2) Close spacing of platy tectonic joints subparallel to the fault surface is fairly characteristic, but extends only a short distance on either side of the fault.

(3) Where displacement can be measured, it ranges generally from 10 to 30 feet (*F* of FIGURE 4), but may be on the order of 100 to 150 feet in the major cross faults (for example, Short Clove, FIGURES 1 and 3). Thompson's estimate of a 350 feet displacement below High Tor (FIGURE 3) appears to be excessive, considering the circumstantial nature of his evidence.

(4) Low-angle feather joints associated with high-angle faults were not observed in connection with any fault exposed in this portion of the Palisades ridge. Consequently, Thompson's interpretation of large flat-lying joints in an outcrop on US-9W (north of the New York-New Jersey boundary) as feather joints inferring the presence of a nearby major fault, appears to be in error. Such joints are more likely to be cooling joints parallel to a buried or eroded contact surface.

Erosional "notches" cut through the Palisades ridge are not necessarily proof of faulting. A case in point is the normal fault east of the West Nyack quarry (right-hand *F* of FIGURE 1), which crosses the crest of the ridge at an elevation of 350 feet in a NS direction. Long-term subaerial erosion in this exposed position aided by glacial scouring has only produced a ravine about 750 feet long, 200 feet wide at the top and 20 feet at the bottom (width of brecciation zone), with a maximum depth of 50 feet. Glacial striae running the length of both ravine walls attest to the effect of glacial abrasion. Displacement could not be determined, but is probably of the same magnitude as the parallel fault to the west (*F* of FIGURE 4). Recent extension of the quarry operation exposed this fault in two opposite quarry faces revealing a gouge zone 10 to 15 feet wide, with a displacement of approximately 25 feet. Close spacing of joints parallel to the fault extends only about 15 feet either side of the brecciation zone. Feather joints are nowhere in evidence.

At the extreme northwest end of the Haverstraw quarry a brecciation and fracture zone of sufficient extent and magnitude has recently been exposed to indicate the existence of a major cross fault through Short Clove (FIGURE 3).

Similar faults through Long Clove (FIGURE 2) and Trough Hollow (*E* of Rockland Lake, FIGURE 1) must remain conjectural for lack of definitive field evidence.

Contacts. There is agreement among workers in this region that actual contact exposures of the Palisades intrusion are rare, indeed. In some instances contact metamorphism of the country rock and chill zones in the diabase can be used to infer contacts with some degree of accuracy.

I have not observed any exposures of the lower diabase contact in the vicinity of the Haverstraw and West Nyack quarries. In the early 1930s C. L. Petzel, a geologist employed by the New York Trap Rock Corporation, located two such exposures along US-9W between Long and Short Clove, but both have since been buried by talus slides.

The solitary known outcrop of the upper diabase contact is at the West Shore Railroad portal south of Long Clove (FIGURES 1 and 2). A detailed description of this exposure is given by Thompson in his paper and need not be repeated here. I cannot agree, however, with Thompson's interpretation of the evidence. There is no doubt that here the gently dipping sediments (well exposed a short distance south of the portal) are down-faulted along the steep dike contact involving also some slices of fine-grained diabase of the chill zone. However, the assumption of a major longitudinal fault offsetting the diabase intrusion proper to account for the steep backslope of the Palisades in this vicinity does not appear to be warranted by the evidence. Furthermore, the suggested existence of similar longitudinal faults along the backslope both north and south of this locality must, for the present at least, come under the heading of wishful thinking.

A rather extensive drill core program, undertaken primarily to ascertain trap rock reserves, was planned to yield as much information as possible concerning the subsurface shape of the diabase intrusion within the limits of the costly undertaking. Twenty holes were drilled to sea level along section lines running approximately at right angles to the trend of the intrusion. Only Sections *A–A′* and *B–B′* involving data from 11 holes are shown in FIGURE 8. More than 5000 feet of drill cores were examined and logged by the writer with the assistance of S. Schaffel, a colleague from The City College. The results pertinent to the structural interpretation of the intrusion may be summarized as follows:

(1) The lower contact was penetrated by holes D.13 and D.8 (FIGURE 8). In addition, one of the contact exposures mapped by Petzel was used to calculate a 14° southwest dip of the lower contact surface at the southeast end of the quarry. The transgressive nature of the contact is suggested by gentler as well as steeper dips of the sediments compared with the calculated dip of the contact surface. Accurate strike measurements on the sediments could not be obtained.

(2) The attitude of the corresponding contact along Section *A–A′* is inferred from the other exposure mapped by Petzel and the fine-grained (chill zone) nature of the diabase at the bottom of hole D1.9. As Thompson suggests, the lower contact descends from an elevation of approximately 250 feet at Long Clove to about 100 feet above sea level at Short Clove. This feature is also

indicated by the columnar structure exposed on the upper level of the quarry where it appears to "lean" gradually to the northwest as Short Clove is approached (upper left of FIGURE 6).

(3) The upper contact surface was intersected by two closely spaced holes (D.18 and D.17) along Section *A–A′*. The calculated dip of 40° is in close agreement with the steepening of the intrusive sheet suggested by the leaning columns and the contact-parallel cooling fractures (as in FIGURE 7). Not the slightest evidence of any faulting was encountered in either drill core, so that longitudinal faulting cannot be postulated at this locality.

(4) The attitude of the upper contact along Section *B–B′*, on the other hand, is inferential and based primarily upon the evidence supplied by the columnar and contact-parallel joints (FIGURE 7).

(5) At the West Nyack quarry where no comparable drilling program has been undertaken to date, a water well drilled 300 feet north of the last diabase exposure at the quarry entrance (LC of FIGURE 4) encountered trap rock at a depth at 376 feet. This would indicate a dip of approximately 50° north for the upper contact surface.

(6) The calculated stratigraphic thickness of 700 feet plus for the Palisades sheet agrees well with Thompson's estimate.

Conclusions

Information presented in this paper is admittedly inconclusive, but may serve to corroborate the basic concepts of Darton and Kümmel. The sum total of the available evidence suggests to me that the outer rim of the sickle-shaped Palisades ridge is a low-angle semicircular dike gradually transgressing sediments of the Newark Group having equally low dips. Along the inner margin (backslope) of the ridge the sheetlike intrusion appears to steepen rather abruptly into a semicircular feeder dike dipping 40° to 50° toward the "center" of the "sickle." Geometrically, this structure could be likened to the rim of one half of a flaring funnel, somewhat reminiscent of the shape postulated for the Cortlandt Complex intrusive, except that it would be "hollow" in the center.

Acknowledgment

I am indebted to Wilson P. Foss, president of the New York Trap Rock Corporation, West Nyack, N. Y., and his staff for their wholehearted cooperation.

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Discussion of the Paper

Rhodes W. Fairbridge (*Columbia University, N. Y.*): The semicircular section of the Palisades Intrusion north of Nyack is reminiscent of a tilted ring dike. Since the Newark Taphrogeosyncline in this sector shows an axial plunge to the south west, it is to be expected that the southwesterly half of a ring dike (if, indeed, present at all) should be hidden. The shape of such a hidden body should be easily demonstrable by seismic refraction. Semicircular fault traces are extremely rare in nature, except in ring dikes and similar structures associated with cone- (or inverted cone-) shaped fractures associated with vertical expansion or collapse, due to igneous volume changes at depth. Alternatively, sickle-shaped fractures are commonly associated with strike-slip faulting in soft rocks over a more brittle basement; the sickle-shaped pattern of the northern Palisades and the Watchungs supports the dextral transcurrent interpretation of the Ramapo Fault, expressed by several observers. Lowe's valuable demonstration of 45° dips along the inner margin of the northern Palisades Intrusion could be interpreted in either light. The additional radial faulting demonstrated by Thompson is also comparable with such reasoning.

H. D. Thompson: Kurt E. Lowe's conclusion that the Palisades intrusive at the southwest end of the New York Trap Rock Corporation quarry at Short Clove has the attitude of a steeply dipping dike is open to two possible errors. His interpretation that the prominent joints dipping northeast at 50 to 60 degrees are primary columnar joints may be in error. An alternative interpretation is that they are diastrophic in origin and are associated with normal faulting.

Lowe's second argument in favor of the dike structure is the fact that drill records show that the intrusive drops off steeply southwest of the quarry. With the limited number of drill holes that he portrays it is impossible to say whether the steep decline is that of a steeply dipping dike or that of a steeply dipping normal fault.

My interpretation that a normal fault borders the steep slope southwest of the quarry is favored by the fact that joint spacing becomes closer and slickensides more prominent as the southwest end of the quarry is approached. Additional drilling, or seismic studies, would help to clarify the structure.

Kurt E. Lowe (*The City College, New York, N. Y.*): Attention is called to figure 7 of the paper under discussion which shows the very gradual change in the attitude of the columnar joints. H. D. Thompson implies that these joints may be interpreted as diastrophic in origin as soon as they depart appreciably from their usual near-vertical attitude. If that be the case, where then do the columnar joints leave off and the diastrophic joints begin? It is evident that both types are not present in any part of the exposure. Furthermore, the so-called diastrophic joints would have the wrong orientation, if interpreted as feather joints produced by an adjacent, high-angle gravity fault down-thrown on the right (SW).

Even with a limited number of drill holes, it is certainly possible to distinguish between an intrusive and a fault contact by examination of the drill cores. In his own paper, Thompson repeatedly infers faults from such factors as closely spaced joints and brecciation zones. Such features would be readily discernible in drill cores cutting across a normal fault of the magnitude required for Thompson's hypothesis.

Finally, I could not substantiate Thompson's claim of closer spacing of joints and their increased slickensiding upon approaching the southwest edge of the Haverstraw quarry either in surface exposures or drill cores.

ISOTOPIC AGES ON SOME IGNEOUS AND METAMORPHIC ROCKS IN THE VICINITY OF NEW YORK CITY

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Introduction

Within the past ten years age determination by isotopic techniques has become developed to the extent that it may be employed effectively in the solution of fundamental geologic problems. The application of the potassium-argon and rubidium-strontium methods to mica and feldspar and the uranium-lead method to accessory zircon has extended the range of quantitative geochronometry to practically every igneous and metamorphic terrain. The abundance of unsolved problems in the igneous-metamorphic complex in the vicinity of New York City poses a situation particularly inviting for intensive study by these methods. This paper presents some new isotopic data obtained in this area and attempts to evaluate its meaning in terms of the metamorphic history of the region.

The principles involved in age determination based on radioactive decay are basically simple. The rock or mineral must contain a long-lived isotope which is gradually transformed with time into a radiogenic, or stable daughter isotope (TABLE 1). For simple radioactive decay, as in the case of Rb^{87} to Sr^{87}, the apparent age of the mineral is given by the expression

$$t = 1/\lambda \, ln\, (d^*/p + 1), \text{ where}$$
$$d^* = \text{number of atoms of daughter isotope,}$$
$$p = \text{number of atoms of parent isotope, and}$$
$$\lambda = 0.693/\text{half life}$$

K^{40} decays into both A^{40} and Ca^{40}, but only the K^{40}-A^{40} pair is used for quantitative age estimation at the present time.

In the case of the uranium-lead method the independence of the $U^{238} \rightarrow Pb^{206}$ and $U^{235} \rightarrow Pb^{207}$ decay chains and the difference in the U^{238} and U^{235} half lives make it possible to calculate an age from the Pb^{207}/Pb^{206} ratio in addition to normal parent-daughter ratios, Pb^{206}/U^{238} and Pb^{207}/U^{235}. If the uranium or lead has been disturbed in any way during the lifetime of the mineral, the apparent ages calculated from the Pb^{206}/U^{238}, Pb^{207}/U^{235}, and Pb^{207}/Pb^{206} ratios form a characteristic pattern that aids in the definition of the type of alteration and the true age of the mineral.

If the apparent isotopic age is to be the true age, the mineral must have behaved as a closed system, that is, there was no addition or subtraction of parent or daughter during its history. This assumption is often imperfectly fulfilled, the most common type of alteration being a partial loss of daughter isotope. Reasons for loss of daughter may be related to the mineral structure, weathering, or recrystallization of the rock by a subsequent reheating or metamorphic

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* Indicates radiogenic component

† Lamont Geological Observatory Contribution No. 358.

process. Indeed, in areas where the rocks have been partly recrystallized by repeated metamorphic events the whole concept of what is meant by the age of a rock requires careful definition.

All analyses reported here were done by isotope dilution, mass spectrometric techniques described elsewhere (Gast *et al.*, 1958; Carr and Kulp, 1957). The standard analytical error for each determination is on the order of 3 to 5 per cent. Deviations from the true age may be caused by geological processes such as partial recrystallization or weathering which, if present, must be detected by a comparison of several isotopic ratios in different mineral phases.

New Jersey-New York Highlands

The New Jersey-New York Highlands comprise a northeasterly trending belt of metamorphic and igneous rocks extending from Reading, Pa., to the Connecticut border. Lower Cambrian sedimentary rocks rest unconformably upon the Highlands complex, thus establishing its Pre-Cambrian age. Later movement has resulted in the preservation of downfolded and downfaulted Paleozoic inliers. FIGURE 1 shows a portion of the Highlands southwest of the Hudson River from which samples for age determination were collected. Mica was separated from a number of rock types, including intrusive granite, pegmatite, marble and several gneiss units. The results (TABLE 2) give apparent ages that range from 765 to 895 million years (m.y.). The experimental uncertainty of approximately ± 30 m.y. for each determination is responsible for part of the spread in the ages; the rest must be geologic in origin. The general agreement between the K-A and Rb-Sr determinations suggests that some sort of metamorphic event occurred in the Highlands around 850 ± 50 m.y. ago. Slight argon loss due to reheating during a later event (see below) could account for the low K-A age of the Lake Tiorati pegmatitic biotite.

TABLE 1
NATURALLY OCCURRING PARENT-DAUGHTER PAIRS USED IN AGE DETERMINATIONS

Parent isotope	Daughter isotope	Half life (yr.)	λ (yr.$^{-1}$)
U^{238}	Pb^{206}	4.49×10^9	$(\lambda\alpha)\ 9.72 \times 10^{-10}$
U^{235}	Pb^{207}	7.13×10^8	$(\lambda\alpha)\ 1.54 \times 10^{-10}$
Th^{232}	Pb^{208}	1.39×10^{10}	$(\lambda\alpha)\ 4.99 \times 10^{-11}$
Rb^{87}	Sr^{87}	5.0×10^{10}	$(\lambda\beta)\ 1.39 \times 10^{-11}$
K^{40}	$A^{40} + Ca^{40}$	1.28×10^9	$(\lambda\beta)\ 4.72 \times 10^{-10}$ $(\lambda\epsilon)\ 0.584 \times 10^{-10}$

Uranium-lead ages to the southwest between the Franklin-Sterling area and the Delaware River have also been determined (TABLES 3 and 4). These ages show a characteristic lead-loss pattern, that is, the Pb^{207}/Pb^{206} age > Pb^{207}/U^{235} age > Pb^{206}/U^{238} age whenever lead has been partially lost from the sample. It can be concluded that the true age cannot be less than 900 m.y., and probably is considerably higher.

Tilton *et al.* (1958) have recently reported U-Pb and Th-Pb ages on zircon, and K-A and Rb-Sr ages on biotite from the Canada Hill gneiss and Storm

King granite at Bear Mountain, N. Y. Their one K-A and two Rb-Sr ages fall in the same range as those shown for different samples of these rocks in TABLE 2. The U-Pb isotopic ages they obtained on the Canada Hill zircon are nearly concordant, indicating an age of about 1150 m.y. Since concordance is usually a severe test of the absence of alteration, this date may

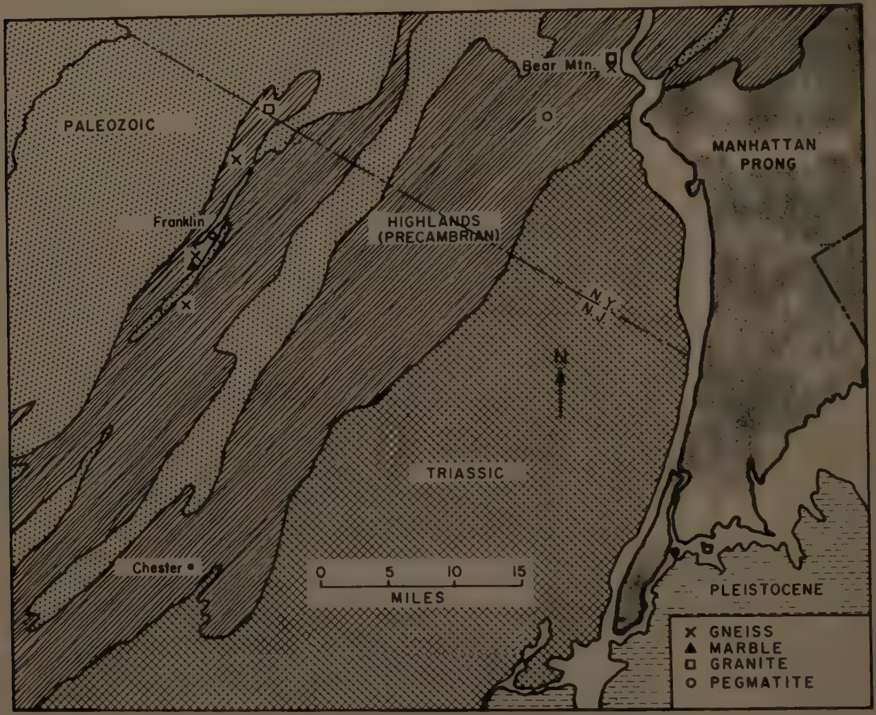

FIGURE 1. Location of samples for isotopic ages, New Jersey-New York Highlands.

TABLE 2
NEW JERSEY-NEW YORK HIGHLANDS MICA AGES

Rock unit	Mica type	Apparent age (m.y.)	
		K-A	Rb-Sr
Sterling Mine:			
"black rock"	Biotite	795 ± 30	
ore body	Phlogopite	895	
Franklin Mine, pegmatite	Mn-biotite	810	
Losee gneiss	Biotite	830	895 ± 30
Biotite gneiss	Biotite	820	
Mt. Adam granite	Biotite	840	
Lake Tiorati, pegmatite	Biotite	765	
Storm King granite	Biotite	850	
Canada Hill gneiss	Biotite	865	870 ± 30

represent the time of initial basement formation in this region. The ages on the Storm King granite zircon are slightly discordant with a pattern suggesting lead loss. The apparent Pb^{207}-Pb^{206} age of 1060 m.y. probably represents a minimum. The Th-Pb ages in both samples are distinctly lower than the U-Pb ages, a common phenomenon attributed to the fact that thorium is inhomogeneously distributed throughout the zircon in such a way that thorium-produced lead is much more easily leached.

One explanation of the U-Pb data is that the minerals initially crystallized in the primary metamorphic event 1100–1200 m.y. ago and experienced slight lead-loss during a later Pre-Cambrian metamorphic event.

TABLE 3

NEW JERSEY-NEW YORK HIGHLANDS URANIUM-LEAD AGES

Rock unit	Location	Mineral	Apparent age (m.y.)		
			Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}
Franklin marble (?)	Phillipsburg, N. J.	Uraninite	825 ± 20	845 ± 25	915 ± 30
Losee gneiss	Chester, N. J.	Monazite	720 ± 25	755 ± 35	900 ± 70

TABLE 4

U-PB ANALYTICAL DATA

	Pb	U	Pb isotopic composition			
			204	206	207	208
	%	%				
Uraninite	7.52 ± 0.010	53.4 ± 1.5	∼ 0.02	100	7.23 ± 0.06	13.8 ± 0.16
Monazite	0.316 ± 0.003	0.232 ± 0.008	0.17 ± 0.01	100 ± 1.5	9.43 ± 0.20	1197

The fact that the zircon ages are higher than the mica and uraninite ages suggests that zircon, being rather resistant to alteration once it is formed, preserves the record of the early metamorphic episode, while the other minerals, being more easily recrystallized, have been altered by a later event. An alternative hypothesis is that the Highlands rocks, formed initially 1200 m.y. ago, were slightly reheated by the profound 365 m.y. metamorphism known to have occurred a few miles to the east in the Manhattan Prong. This interpretation appears less likely, at least in the Franklin-Sterling area where some of the samples were collected near Cambro-Ordovician sedimentary rocks that are folded, but otherwise show no signs of having undergone metamorphism. Of course the Highlands rocks were at depth 365 m.y. ago, and the possibility remains that a very gentle reheating at that time could have left the Lower Paleozoic sedimentary rocks virtually unaffected, while lowering the Highlands mica ages from a true value of about 1200 m.y. to an apparent value of 800–900 m.y. Experience with a similar transition zone in the Southern Appalachians (Long *et al.*, in press) makes it quite unlikely that in such a process the Rb-Sr and K-A ages would agree as they do in the Losee and Canada Hill samples.

A word of caution is necessary. The age spread due to the unknown extent to which the isotopic ratios have been altered subsequent to the period of metamorphism makes it impossible to ascertain the fine structure of events within the metamorphic cycle. For example, at Bear Mountain it is known on geologic grounds that the Storm King granite is intrusive into the Canada Hill gneiss (Lowe, 1950), but it is impossible to infer this age relationship from the isotopic data. Nor can the available isotopic measurements be used to infer whether the original rocks were sedimentary or igneous.

Manhattan Prong

The rocks of the Manhattan Prong consist of basal Fordham gneiss overlain in turn by the Inwood marble and Manhattan schist and gneiss. The problem of assigning the stratigraphic age of the New York City group is outside of the scope of this paper. Samples were collected for K-A determinations from all the major rock units (Long and Kulp, 1958; FIGURE 2). The first nine K-A ages (TABLE 5) closely group within the experimental uncertainty of about ± 15 m.y. The agreement among these diverse mineral types suggests that the average apparent age, 365 m.y., is close to the true age for the latest metamorphic event. On uraninite from the Branchville, Connecticut pegmatite which gave reasonably concordant U-Pb ages (Wasserburg *et al.*, 1956) the U^{235}-Pb^{207} decay gave 365 m.y. On two samples of zircon from the Bedford, New York pegmatite, also in this area, Nier (1939) obtained U^{235}-Pb^{207} ages averaging 355 m.y.

The older K-A age of 440 m.y. from the Fordham formation is anomalous and indicates an earlier metamorphism in the Manhattan Prong whose record was not completely obliterated by the 365 m.y. event. The age must be considered a minimum because of the proximity of the sample to the zone of complete recrystallization at 365 m.y.

From these data it may be concluded that the Manhattan Prong underwent a profound period of metamorphism and igneous intrusion about 365 m.y. ago. Just as in the Highlands, nothing about the date of original sedimentation may be inferred from the age data except that it occurred prior to the metamorphism. The older K-A age in the Fordham gneiss strongly suggests an earlier metamorphism. The question is whether the Manhattan Prong represents Pre-Cambrian (Grenville-equivalent?) rock from which earlier accumulated argon was generally baked out at 365 m.y., or whether these rocks were deposited in Lower Paleozoic time and metamorphosed by a separate but earlier event around 450–500 m.y. ago. Strict definition of the time of an earlier metamorphism would be difficult because of the thoroughness with which the 365-m.y. event has recrystallized the rock. There are no zircon data yet available on Manhattan Prong rocks. Investigation in this area is being continued.

Highlands Transition Zone

Naturally, the border zone between two provinces so widely divergent in age would be expected to show some interesting anomalies. K-A ages on mica

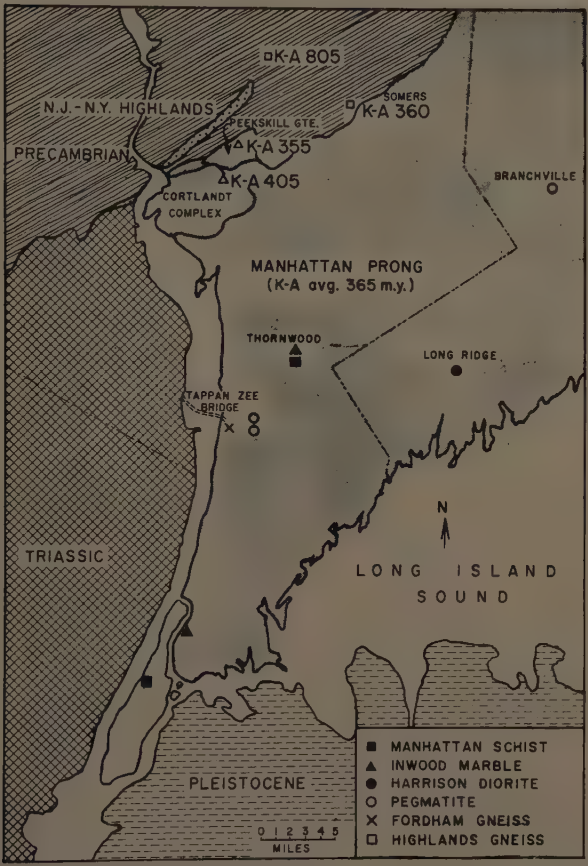

FIGURE 2. Location of samples for potassium-argon ages, Manhattan Prong.

TABLE 5
MANHATTAN PRONG POTASSIUM-ARGON AGES

Location	Formation	Mica type	Apparent age (m.y.)
Bronx	Inwood	Phlogopite	355
Manhattan	Manhattan	Biotite	360
Thornwood, N. Y.	Manhattan	Biotite	380
Thornwood, N. Y.	Inwood	Phlogopite	350
Long Ridge, Conn.	Harrison	Biotite	375
Branchville, Conn.	Pegmatite	Muscovite	365
		Muscovite	365*
Tarrytown, N. Y.	Pegmatite	Biotite	370
		Muscovite	370
			Average 365 ± 10 S. D.
Tarrytown, N. Y.	Fordham	Biotite	440

* Analysis by Wasserburg, Hayden, and Jensen (1956).

from two igneous bodies, the Cortlandt Complex, a funnel-shaped basic intrusion that cuts the Manhattan formation with a contact-metamorphic aureole along the border, and the Peekskill granite, an intrusive younger than the Cortlandt Complex, have been determined (FIGURE 2). The Peekskill granite age of 355 ± 15 m.y. correlates with the 365-m.y. event mentioned previously. The higher apparent age from the Cortlandt Complex is again suggestive of an older metamorphism in the Manhattan Prong. Very likely, it is an anomalous age reflecting the extent of recrystallization of the original biotite by the later metamorphism. In this case the Cortlandt ultramafic intrusion was probably related to the primary metamorphic event. More work is needed to test this hypothesis.

Northeast of Peekskill the Highlands pass into the area totally affected by the 365 m.y. metamorphism. A sample of Pre-Cambrian Highlands biotite near the Highlands-Manhattan Prong border at Somers has been so thoroughly recrystallized as to give an age identical to those from the Manhattan Prong. Eight miles to the northwest, however, perpendicular to the strike of the zone of Paleozoic metamorphism, Highlands biotite has retained nearly all of its argon, giving an apparent age of 805 m.y. Presumably, samples taken between these two localities will have apparent ages between the two, related to the extent to which the daughter isotope has been lost from the mica during the 365 m.y. event.

From the present data it is tentatively concluded that the metamorphism of the New Jersey-New York Highlands began 1100–1200 m.y. ago. Another regional event occurred about 850 m.y. ago which recrystallized the mica in the metamorphic rocks of the entire area, but was not of sufficient magnitude to cause serious chemical alteration of the zircon. The latest recrystallization of Manhattan Prong rocks occurred about 365 m.y. ago; scattered evidence points to a metamorphic history of these rocks prior to that time. Northeast of the Hudson River where the Highlands have been strongly remetamorphosed in Lower Paleozoic time, apparent ages between 1200 m.y. and 365 m.y. are found.

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STRATIGRAPHIC POSITION OF THE LOWERRE QUARTZITE

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In historical perspective, the Lowerre quartzite question breaks down into two separate problems. FIGURE 1, an index map of southeastern New York State shows the locale for the first problem: whether the existence of a quartzite found on preliminary mapping south of the Hudson Highlands in the presumed sequence: quartzite-metamorphic limestone-schist means that these rocks can be correlated with the apparently less metamorphosed quartzite-limestone-phyllite sequence north of the Hudson Highlands (Merrill *et al.*, 1902). This problem has been hotly discussed up to the present day. The general contemporary opinion seems to be that such speculation, while interesting, is incapable of final decision with the information available to us at the present time. Most who have considered this correlation problem feel that the solution must lie in more detailed studies of the intervening area of the Hudson Highlands, especially of the eastern part where topographic lows suggest the possibility of structural breaks in the continuity of the Highlands Massif, through which direct physical correlation may be possible. However, even the western part of the Highlands may still provide surprises as, for example, the recent discovery of a considerable outcrop area of highly metamorphosed quartzite capping the hills north and northwest of Nelson Pond (Schreiber, 1958).

The second problem concerning the Lowerre quartzite, the one to which I shall address myself chiefly here, is whether it exists and, if it does, its method of origin and stratigraphic position.

Berkey (1907) first raised the question whether the quartzite, as previously reported, overlay the gneiss as part of a quartzite-metamorphic limestone-schist sequence, or whether it might not be an upper, more quartzitic member of the Fordham gneiss. Thus, if the Fordham gneiss were overlain unconformably by the Inwood metamorphic limestone, this would explain why the Lowerre quartzite did not always appear to be present between the gneiss and the metamorphic limestone. Fluhr and Bird (1939), reporting on an occurrence of Poughquag quartzite near Hortentown and of Lowerre quartzite near Somers, reported that a pebbly quartzite appeared to grade into gneiss through a fine-grained quartzite, which in thin section proved to be a sheared and cemented granite. Shearing of this nature is to be expected at the top surface of competent material during deformation (Brace, 1958). Dana in an earlier study (1881) mentioned a quartzite that appeared to grade laterally into a granite, but in this case he attributed the granite to a process of what we should now call granitization. More recently Prucha (1956) stated (1) that the Lowerre quartzite, where found, had wholly developed locally by shearing of the Fordham gneiss and was in fact within that formation, (2) that the Fordham gneiss itself is in stratigraphic continuity with the Inwood metamorphic limestone and the Manhattan schist, and (3) that, with the exception of the Sparta and Hastings localities, no rock that even looks like a quartzite exists at the previously reported locations, including the type locality. Norton and Giese (1957), however, listed localities where the quartzite could be seen, and included a photograph of the Lowerre quartzite at the type locality.

The answer to the question: "Is there a quartzite?" is of prime importance to our study. FIGURE 2 shows the locations at which a quartzite has been reported and where, on examination, such a formation was found to exist. In addition, the one subsurface measurement given is taken from well log WE 144 described by Asselstine and Grossman (1956). Other subsurface occurrences of the quartzite have been mentioned informally to me but, lacking official confirmation, are not reported here. Descriptive data of most outcrop localities have been briefly given by Norton and Giese (1957) (TABLE 1). There is a quartzite or quartzite-appearing rock at each locality listed.

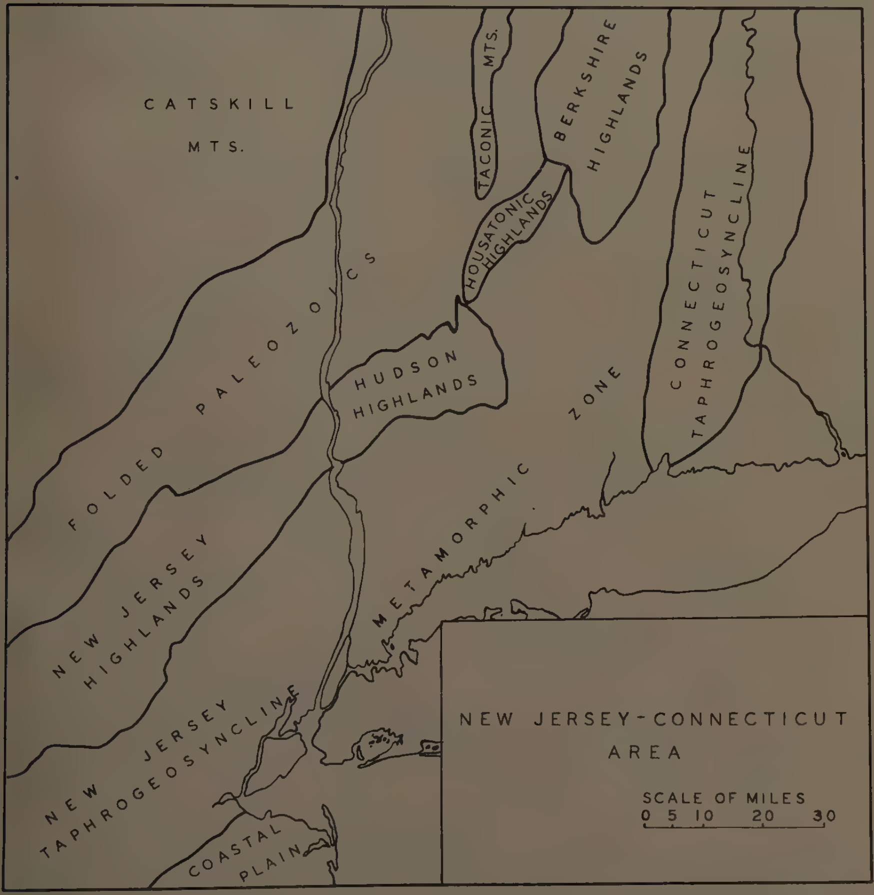

FIGURE 1. Index map showing location of metamorphic zone in which the quartzite occurs.

The next question to be answered, then, is: "If we accept the existence of

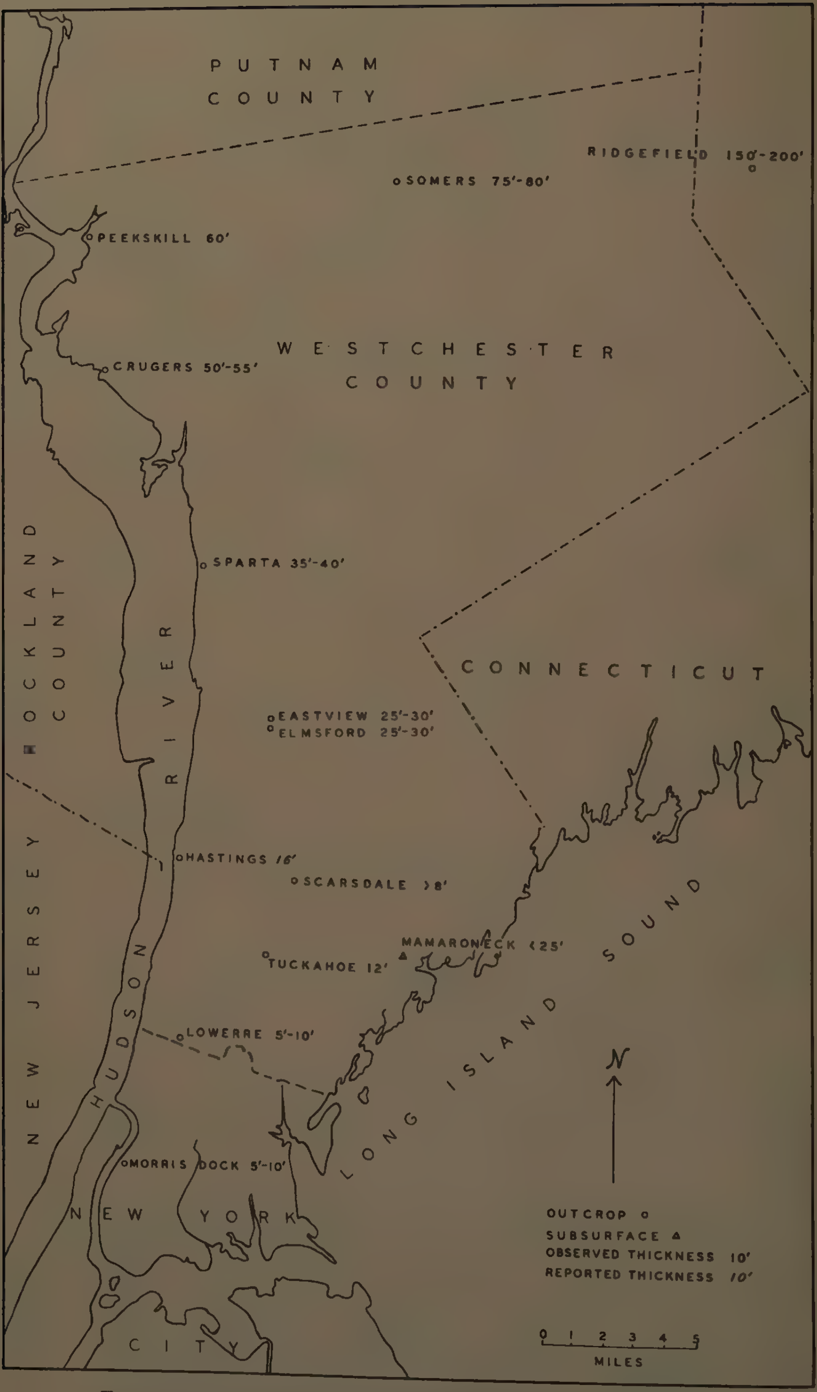

FIGURE 2. Quartzite outcrops in southeastern New York State.

this quartzite, what is its origin?" One of the best quartzite localities was not exposed at the time the 1957 report by Norton and Giese was prepared. A preliminary description of this occurrence may shed some light on the question of the origin and stratigraphic position of the quartzite. A few hundred yards south of the known quartzite outcrop at Eastview, The Great Atlantic and Pacific Tea Company recently constructed a large warehouse complex at Elmsford, N. Y. In doing so, they cut back into the hillside, exposing the quartzite and its contacts. Through the kindness of T. J. Lynch, superintendent of operations at the warehouse, I was able to visit this area and examine it in some detail. The exposure (FIGURE 3) is almost 1400 feet long and in detail shows great structural complexity. The warehouses themselves are built chiefly on the weathered limestone and glacial fill of the valley. The hill behind them has been cut back in two steps and above this has been scraped bare of superficial loose material, exposing both gneiss and quartzite. Farther up the hill only gneiss is present. In the cut itself gneiss, quartzite, pegmatites, and weathered limestone are exposed. FIGURE 4 is a closer view of part of the cut, showing on one side well-bedded, jointed quartzite and, on the other, a zone of shearing that includes contorted pegmatitic material. FIGURE 5 is a detailed view of red and green color banding in a more massive part of the quartzite.

TABLE 1

LOCATION OF LOWERRE: DESCRIPTIVE DATA OF QUARTZITE OUTCROPS

Crugers: On the south side of Maiden Lane in the bed of Furnace Brook below the lowest dam.
Eastview: On the west side of the railroad cut 1⅝ miles south of Eastview station, measured along the tracks of the Putnam Division of the New York Central Railroad.
Hastings: On and behind the hanging wall of the quarry on the east side of the road running along the Old Croton Aqueduct.
Lowerre Station: About 20 feet south of Lawrence Street in the abandoned railroad cut east of Saratoga Street.
Morris Docks: 200 yards south of the Morris Heights station on the east side of the railroad cut just below the New York Thruway.
Peekskill: Poughquag quartzite on the southeast bank of Peekskill Creek. This outcrop has been called Poughquag quartzite on the basis of the low rank of metamorphism of the overlying pelite. It might be just as reasonable to assign it to the Lowerre on geographic location. It is included here because its thickness seems to fit the continuous pattern of thicknesses of the quartzites south of the Hudson Highlands.
Ridgefield: On the hill west of New Road which runs west from U. S. Route 7, 1.4 miles south of its junction with Connecticut Route 35; the quartzite is well exposed in a cliff on the northwest side of the southern part of the hill and in ledges on the southeast of the central part of the hill, but no contacts are exposed. This outcrop was first located by James M. Clarke.
Scarsdale: 900 yards north of Scarsdale on the west side of its junction with New York Route 100; the quartzite is here overturned and lies under what is usually identified as "Highlands gneiss". There is a difference of 10 to 15° in places between the lineations of the gneiss and the bedding of the quartzite.
Sparta: 260 yards south of the old Sparta Landing on the east side of the tracks of the main line of the New York Central Railroad; vertical beds exposed northwest of Sparta Brook.
Tuckahoe: In the west wall of the old Norcross Brothers Marble Quarry.

As reported by Norton and Giese (1957), the quartzite in the Eastview outcrop had a stratigraphic thickness of 25 to 30 feet. As its continuation is exposed in most parts of the Elmsford cut, this appears to be a reasonable average. However, in one spot there is an anomalous 75-foot thickness of quartzite. There is probably some structural explanation of this apparently excessive thickness, since there are small sheared zones and a pegmatite within this thickness. Immediately below this thickness of quartzite are 15 feet of

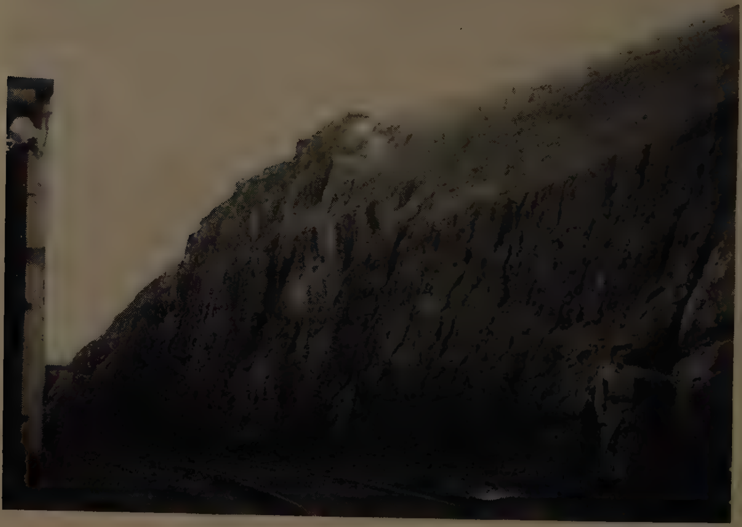

FIGURE 3. Exposure of quartzite at Elmsford.

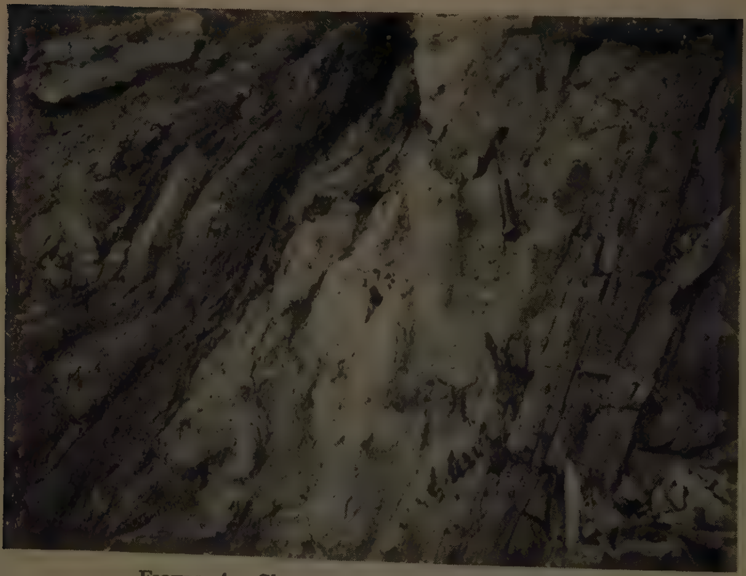

FIGURE 4. Close-up view of quartzite outcrop.

well-sheared pegmatite, 35 feet of sheared gneiss, and 4 feet of unsheared pegmatite, all lying on a weathered banded gneiss.

TABLE 2 shows data from preliminary petrographic examination of 15 thin sections taken from this 75-foot exposure of quartzite, plus one from the sheared gneiss below and one from an included pegmatite. Note that the quartzite here varies from arkosic to quite quartzose material. The thin sections do not show signs of the crystal orientation that would be expected if it has a tectonite origin. There is a notable difference in the texture and mineral content between the sheared gneiss and the quartzite.

Let us return now for a moment to FIGURE 2. In every case where the lower contact of the quartzite is clearly exposed, it is structurally discontinuous with the underlying gneiss, with either faulting, shearing, or bedding plane and other pegmatites intervening. In some outcrops the foliation of the quartzite parallels that of the gneiss; in others it does not. At Somers, Conn., there is a 10 to 15° difference in places between the lineations of the gneiss and of the quartzite. This may represent an actual unconformity. Within the quartzite itself there are bands with micaceous, presumably originally argillaceous, partings in the middle part of the formation. There is what appears to be remnant cross-bedding, possibly of fluvial origin at Somers. At Sparta, N. Y., much of the formation is cross-bedded; cross-bedding which is clearly aeolian is exposed at one spot near the river. The color banding at Elmsford may or may not represent a primary feature.

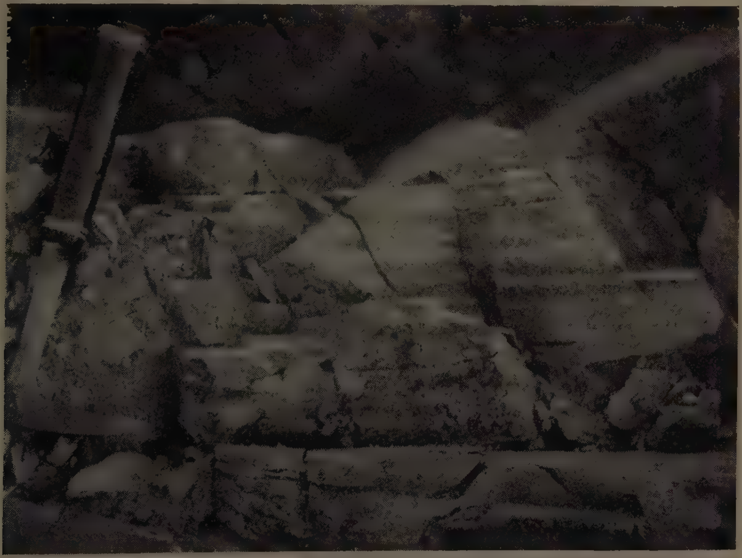

FIGURE 5. Color banding in quartzite.

The upper contact between the quartzite and metamorphic limestone, while usually not exposed due to differential erosion, appears in the new cut at Elmsford to be a normal sedimentary one with quartzite bands occurring interbedded in the limestone. This, the primary features listed above, and the lack of tectonic fabric in the quartzite indicate a sedimentary origin. The next question is: "Can these outcrops be thought of as being parts of a single formation?"

TABLE 2

PRELIMINARY PETROGRAPHIC DATA ON ELMSFORD OUTCROP OF LOWERRE QUARTZITE

(Mineral percentages)

No.	Location	Quartz	Microcline	Plagioclase	Biotite	Muscovite	Sphene	Others
1.	Sheared gneiss	20–25	55–60	5–10	10			Micropegmatite
2.	Base of quartzite	98	1				<1	Monazite, zircon
3.	In quartzite immediately below included pegmatite.	40–45	35–40	5–10	5			
4.	At upper margin of pegmatite	60–65	15–20		10–15	<1	<1	Magnetite, zircon monazite
5.	Quartzite 2 inches above pegmatite	15–20	70–75		5	<1		Hematite, magnetite Micropegmatite
6.	Quartzite about 5 feet above pegmatite	70–75	15–20	5	5	<1	<1	Magnetite
7.	Quartzite about 15 feet above pegmatite	70–75	10–15		5–10	<1	4–5	
8.	Quartzite about 25 feet above pegmatite	45–50	20–25	5–10	10–15			
9.	Quartzite about 35 feet above pegmatite	75–80	10–15		<1	5	<1	
10.	Quartzite about 45 feet above pegmatite	80–85	5–10	5	5		<1	Magnetite, micropegmatite
11.	Quartzite about 55 feet above pegmatite	50–55	30–35	5–10		<1		Pyroxene
12.	Quartzite about 60 feet above pegmatite	80–85			5			Micropegmatite, 5–10% opal
13.	Quartzite about 65 feet above pegmatite	40–45	30–35	10–15			5–7	
14.	Quartzite in area with red and green color banding	45–50	35–40		5		<1	Hematite 2–3%
15.	Near top of quartzite	95						Chalcedony, hornblende, micropegmatite
16.	Sheared zone above 15 feet	75–80	10–15		5			
17.	Sheared lower zone within quartzite	90				<1		5–10% opal

In dealing with deformed, unfossiliferous, metamorphic rocks, the minimum requirements for assuming that material occurring in several isolated outcrops constitutes a true formation should be that the rocks in question are:

(1) Reasonably distinct in lithology.

(2) Reasonably stable as to stratigraphic position.

(3) Reasonably widespread in extent, and that

(4) They might have been reasonably continuous prior to deformation. Continuity is not the most frequently used nor the most reliable criterion, since sedimentary formations (for example, the Oriskany sandstone) are not always continuous in extent.

Let us apply these criteria to the quartzite outcrops considered here.

(1) In hand specimens the rock is distinctly a quartzite. In many places it weathers brown. Under the petrographic microscope it proves to vary from rather pure quartzite to what must have originally been an arkose.

(2) The stratigraphic position of the quartzite as observed is always between the metamorphic limestone and gneiss. No quartzite beds of similar thickness have been reported within the gneiss or within the limestone.

(3) FIGURE 2, which gives known localities, shows them to be reasonably widespread.

(4) The same illustration appears to suggest a possibility that the formation was originally continuous and thickened generally toward the northeast, but the data are too few to enable us to reach a firm conclusion. If we are to apply the criterion of original continuity strictly, is it reasonable to expect that the quartzite now always be found between the gneiss and metamorphic limestone? I believe it is not. We already noted that at all localities there is a "structural unconformity" (Balk, 1936) between the gneiss and quartzite. There is, therefore, the possibility that the quartzite would now be missing in some localities for structural reasons. The exposure of an unsuspected area of quartzite by warehouse construction at Elmsford also indicates that glacial cover or natural weathering may preclude natural outcropping of the quartzite. In fact, six of the known localities have been exposed only by construction of some sort. Further such man-made exposures will probably occur in the future in locations where, on sound structural grounds, the quartzite may be expected to exist.

Let us summarize our conclusions thus far. The quartzite exposures south of the Hudson Highlands do exist; they appear to be of sedimentary origin; and, in light of present evidence, they constitute a bona fide formation. Therefore, unless or until future data render these conclusions invalid, the established formation name—Lowerre quartzite—should continue to be applied to them.

There is one more matter to be considered in connection with the Lowerre quartzite which, while it may not prove so controversial, may eventually be more productive of worthwhile conclusions. This is the nature and cause of the present structural pattern of the quartzite. In style of deformation the quartzite appears to have behaved less competently than the underlying gneiss. In all cases it has deformed by folding with, possibly, some bedding-plane thrusting, while the gneiss often appears to have fractured or to have had its top section sheared due to the movement of overlying beds. Similar shearing has been reported from other regions (Brace, 1958). At Scarsdale, N. Y., Sparta, and Elmsford the limestone appears to have yielded to deformational stresses by folding, but on a larger scale and with different orientation than the quartzite. For example, at Elmsford the limestone belt, if it is, as suggested by Merrill *et al.* (1902), representative of one limb of a large fold, strikes about N 35 to 40° E, with the causative direction of compression resolving to about N 50 to 55° W. In contrast, the structures in the quartzite appear to consist of a number of smaller-scale pleat folds plunging about 60 to 75° in the southeast direction. These would require a more north-south oriented direction of compression. The weathered gneiss at the very northernmost part of the exposure strikes N 5° W, possibly requiring still another tectonic direction, and does not appear to have entered into the pleat folding of the quartzite. There are several possible theoretical solutions to the structural enigma posed by these observations, but from the information presently available it is impossible to select the correct answer.

In this, as in all of the problems raised by the quartzite, our need is for more data. With this in mind, I suggest three levels of investigation that would cast light on a number of minor and major problems which confront us in the New York area.

Since the immediate concern of this paper is with the Lowerre quartzite, the first level I shall mention involves further clarification of the problems posed by this formation.

(1) We should set up a carefully directed program of exploration (including trenching, if necessary) to discover the extent of the quartzite at known localities, and to uncover new areas. In the latter case, exploration should be guided by a knowledge of the general structure of the region.

(2) Each quartzite locality should be carefully mapped in detail to work out the finer points of structure and stratigraphy.

(3) There should be careful detailed sampling and subsequent heavy mineral studies, thin section, and petrofabric analyses of the quartzite and surrounding rocks at all locations.

A prerequisite to step 1 listed above is a general knowledge of the broad structural pattern of the New York area, but such a picture is not available on the basis of published data. The old *New York Folio* (Merrill *et al.*, 1902), as we all know, is based on reconnaissance mapping, and could no doubt be greatly revised merely on the basis of the local knowledge of the contributors to this monograph. Hence, on the second level of investigation I suggest the following:

(1) We should pool our special local knowledge, as well as our concepts of the general geology, stratigraphy, and structure of the area.

(2) On the basis of this information we should draft a working map or maps (depending on the degree of agreement that can be reached) of the area as a guide to further work. Also, the alternative stratigraphic and structural hypotheses should be brought together side by side in one preliminary publication. Both the map and multiple working hypotheses as to structure and stratigraphy should be made available to anyone working in the area.

(3) We ourselves should undertake detailed studies in critical areas or subjects in the region, and encourage students likewise to do honors work, masters' theses, and doctoral dissertations of a similar nature. Certainly, there is a plethora of subjects available. Many come to mind: the further work on the Lowerre quartzite, the differentiation of the various lithologies now lumped together as the Fordham gneiss, a similar study of the Inwood metamorphic limestone, a study of palimpsest primary features, a study of the nature of the metamorphism shown in the area, further comparative dating of various minerals in critical areas, and many local areal studies which should include detailed mapping and structural, petrofabric, and petrographic analyses. All of these should eventually supply material to produce a new, more accurate map and geologic description of the area.

However, all of this work requires and leads to yet a third level of investigation that deals with subjects of more universal application.

First, to be able to do accurate geologic mapping in any region, we must be able to recognize and distinguish lithologies. The field classification of metamorphic rocks leaves much to be desired; so does the terminology used in laboratory analyses. Often field descriptions and petrographic analyses are expressed in terms so different that it is hard to believe that the same rock is being discussed. An early necessity in the studies proposed, therefore, is the development of a more useful and accurate classification system for metamorphic rocks, one which can be applied to hand-specimen and thin-section analyses alike.

Finally, in addition to the benefits of better understanding our local area, the studies proposed may perhaps lead to a better general knowledge of the often critical relationship between basement and cover in metamorphism and in deformation.

In retrospect, the controversy concerning the nature, identification, and origin of the Lowerre quartzite developed primarily because so many fundamental questions have gone unanswered. I hope that our future energy will be directed toward cooperation in a common effort to solve these problems.

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Discussion of the Paper

Peter Tuozzolo (*New York City Department of Public Works, New York, N. Y.*): A quartzite lying between the Fordham Gneiss and Inwood Marble was encountered in five diamond drill borings made by the New York City Department of Public Works. The borings, located on Palisade Avenue in the Riverdale section of New York, are on a line cutting the strike of the formations by some 20 to 30 degrees. The over-all distance between these 5 borings is approximately 450 feet. Other borings on this line immediately to the north and south do not cross the Fordham-Inwood contact; hence, the maximum strike length of this quartzite is not known.

The quartzite cored in these borings is a gray-white to tan, fine-grained, dense, frequently jointed rock, consisting of 90 to 95 per cent quartz with microcline and magnetite as accessories. The true thickness varies from 3 to 27 feet.

The occurrence of this quartzite corroborates Norton's contention that a quartzite does exist between the Fordham and the Inwood. If this quartzite can be seen at a number of locations, then it would seem that its formational rank is valid.

FIELD RELATIONSHIPS BEARING ON THE AGE OF THE NEW YORK CITY GROUP OF THE MANHATTAN PRONG

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Introduction

For more than a century geologists have debated the age of the metamorphic rocks of the New York City group in southeastern New York. Much of the argumentation has been waged without sufficient cognizance of the regional geology and without detailed knowledge of specific geologic features pertinent to this important problem.

Through a discussion of selected field relationships an attempt will be made here to clarify the existing geologic framework within which the difficult correlation problem must be studied.

Regional Setting

The New York City group (Prucha, 1956, p. 673; Scotford, 1956, p. 1158) consists of the basal Fordham gneiss overlain by the Inwood marble and the Manhattan formation. This metamorphic group, of uncertain age, is exposed abundantly in the Manhattan Prong south of the Hudson Highlands in southeastern New York State. The formations may be traced continuously from New York City north and northeast more than sixty miles to the vicinity of Danbury, Conn.

The New York City group of the Manhattan Prong is bounded on the north by the Pre-Cambrian Hudson Highlands. These highlands are a northeast extension of the Reading Prong and the New Jersey Highlands. The Hudson Highlands cross the Hudson River between Peekskill and Beacon, beyond which the southern border swings to the east-northeast. On the north, the Hudson Highlands terminate in a number of spurs separated by indentations of younger metamorphic rocks. Seven miles north of the prominent spur near Poughquag lies the southern end of the Pre-Cambrian Housatonic Highlands. The village of Wingdale, N. Y., lies between the two Highlands blocks in what has come to be called the Wingdale Gap.

On the north side of the Hudson Highlands, in Dutchess County, is a Cambro-Ordovician sequence consisting of the Lower Cambrian Poughquag quartzite overlain by the Wappinger limestone and the Hudson River pelites. The lower part of the limestone is Cambrian, but the upper part and the pelites are Ordovician (Knopf, 1927).

Balk (1936) and Barth (1936) demonstrated conclusively that the Cambro-Ordovician sequence can be followed eastward through Dutchess County across zones of increasing metamorphism into rocks equal in metamorphic rank and similar in lithology to those of the New York City group.

The geographic relationships of the three terranes defined above are shown in FIGURE 1.

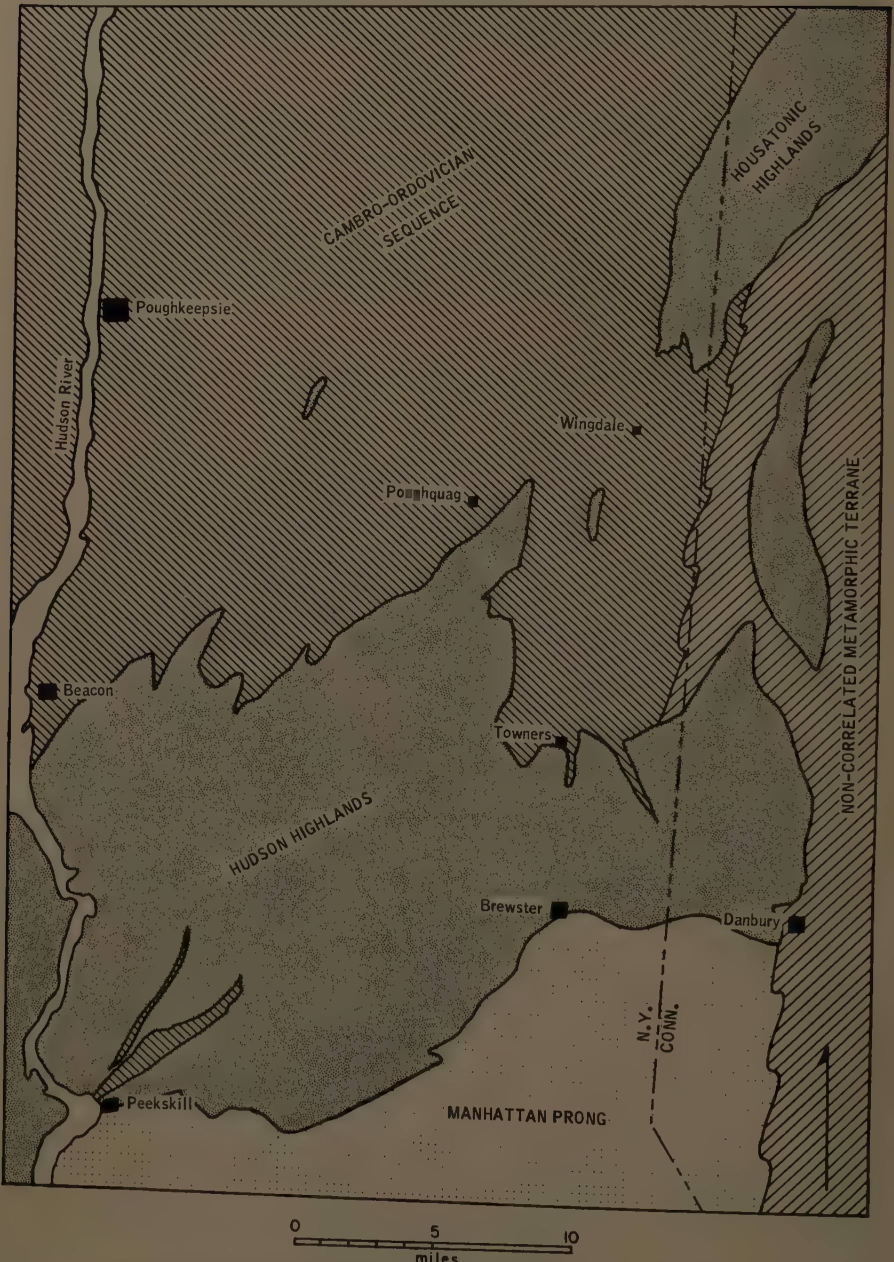

FIGURE 1. Index of geologic terranes in southeastern New York State.

Geology of the New York City Group

The formations. A proper evaluation of the age relationships of the New York City group must be based upon adequate field mapping. Mapping the New York City group is not particularly difficult and, for the most part, excellent topographic bases are available. It should be emphasized, however, that it is necessary to map on an outcrop-by-outcrop basis, and to walk out all contacts from end to end within a map area. Reconnaissance mapping based upon a study of roadside outcrops or upon cross-country traverses along a seemingly appropriate grid can only lead to confusion. In large part this is due to the structural complexities present, but to some extent it is due to the interlayering of lithologic types on an intimate scale.

The present discussion is based principally upon field mapping by the writer in the Lake Carmel, Brewster, Croton Falls, and Peach Lake quadrangles in Putnam and Westchester counties, N. Y. The accompanying geologic map (FIGURE 2) shows in generalized form the results of that work, along with that of D. M. Scotford and R. M. Sneider in contiguous areas of New York and Connecticut.

Within the mapped area, as elsewhere, the Fordham gneiss is the basal formation of the New York City group. The formation is a plagioclase-quartz-biotite gneiss with variable amounts of hornblende, potash feldspar, and garnet. Strong mineralogical layering is characteristic of the gneiss. Thin layers (<2 feet) with granoblastic textures and great persistence along the strike are usual. Interlayered with the gneiss are abundant amphibolite, mica schists, marble, and several types of granite.

The Inwood marble is a white to gray, moderately silicated rock ranging in composition from calcite to dolomite. It commonly contains mica schist bands locally, and has in a few places been injected by granite. The Inwood is indistinguishable lithologically from marble layers occurring within the Fordham and Manhattan formations.

The Manhattan formation is dominantly composed of garnetiferous quartz-biotite-plagioclase gneiss and high-grade mica schists. Sillimanite and muscovite are generally abundant. Amphibolite and marble are common interlayers, and in places the formation is abundantly injected by granitic material. The Bedford augen gneiss is interpreted by Scotford (1956, p. 1177–1179) as a modification of a diorite earlier intruded into the Manhattan formation. The mafic complexes near Croton Falls and Peach Lake also occur within the Manhattan formation; however, like the Bedford augen gneiss, they are not considered part of it.

Nowhere within the area was a mappable quartzite encountered.

Stratigraphic characteristics. The Fordham gneiss, the Inwood marble, and the Manhattan formation are valid formations in a regional sense, but anyone who has done any detailed mapping within the group must be aware that an intimate interlayering of the several lithologic types is characteristic. Especially common are rocks of Manhattan-type and Inwood-type lithologies interlayered with the dominant Fordham lithology in Fordham gneiss belts, and Inwood-type rocks interlayered with the Manhattan-type lithologies in the Manhattan formation belts. This interlayering of lithologic types occurs on a wide range of scales, with interlayers ranging in thickness from a few inches to tens of feet. In some localities the alternation of lithologic types across contacts is so well developed that formation boundaries must be arbitrary.

In a few localities the interlayering of lithologic types may be the result of tight infolds of one lithology into another but, in most cases, the lack of mirror repetition of rock types on opposite sides of the axis of any presumed infold rules aginst the interpretation of the interlayering being a result of severe folding. Furthermore, the contacts between two separate layers are commonly gradational and thus suggest a continuous change in the composition of the original sediments near the interface.

TABLE 1

SECTION BELOW TITICUS RESERVOIR DAM

Lithologic type	Thickness in feet
Top	
Manhattan	2.5
Inwood	1.5
Manhattan	69.5
Inwood	19.5
Fordham	54.0
Inwood	3.0
Fordham	54.0
Inwood	6.0
Fordham	1.0
Inwood	0.2
Fordham	21.0
Inwood	0.1
Fordham	2.0
Inwood	0.2
Fordham	49.0
Bottom	

Such alternation of lithologic type has been recognized by a number of workers in the area (Berkey and Healey, 1911; Fluhr, 1941; Kemp, 1910; Scotford, 1956, p. 1160), but its significance has not been sufficiently emphasized.

The section exposed along the Titicus River immediately below the Titicus Reservoir dam at Purdy's, N. Y., illustrates well the intimate small scale interlayering of distinct lithologic types characteristic of the New York City group (Prucha, 1956, p. 676). At this location the New York City group is exposed continuously for 283 feet across vertical layers. The sequence exposed is shown in simplified form in TABLE 1.

The type of interlayering described here reflects an alternation in the type of original sediments deposited. It reflects a shift from dirty sands through carbonates to argiliaceous sediments,* with numerous oscillations from one sediment type to another during deposition. As might be expected, the various combinations of lithologic types differ from one locality to another and are most pronounced close to the contacts between the formation belts.

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* Scotford (1956, p. 1181–1184) considers the premetamorphic equivalents of the Fordham gneiss, Inwood marble, and Manhattan formation to be, respectively, graywacke, cherty limestone with interbedded shale, and an alternating sequence of siltstone and shale. His conclusion is based upon chemical evidence, textures, and rock associations.

The conformable and wholly integrated relationship existing among the three formations of the New York City group, as described above, is consistent throughout the area mapped by Scotford, Sneider and myself. Insofar as is known, the Fordham gneiss is conformable with the Inwood marble and Manhattan formation throughout the traceable extent of the New York City group.

Structure. Within the area mapped, the New York City group has behaved structurally very much as a single unit. All three formations have been deformed simultaneously and, in general, they all belong to the same metamorphic facies. Slight differences in behavior among the several rock units during deformation are clearly related directly to different inherent mechanical properties, such as plasticity, rather than to different deformation histories. For example, the Inwood marble behaved very plastically during deformation, and flowed readily during the folding of the rocks. This accounts in large part for the wide range in thickness of the marble belts which, in places, have been completely squeezed out from between the Fordham gneiss and the Manhattan formation at the present level of erosion. The commonly observed shearing along Fordham-Inwood and Inwood-Manhattan contacts reflects differences in competence between adjacent rocks, and should not by itself be considered evidence of faulting.

The New York City group is bounded on the west by a major high-angle fault that separates the Pre-Cambrian rocks of the Hudson Highlands from the younger New York City group on the east. From New York City to the vicinity of Bedford the dominant structure of the New York City group is a series of isoclinal folds trending north-northeast, with the axial planes dipping steeply to the northwest. Between New York City and Bedford the plunge of the structures changes back and forth from south to north several times.

From Bedford northeastward the axial planes of the folds have themselves been folded to produce great arcuate belts of New York City group formations. Scotford (1956, p. 1190–1197) was the first to recognize this structure in the area, and applied to it the term axial-plane folding. It is not known whether this second stage of folding is the result of a separate period of deformation, or whether it took place late in the same period of orogeny that produced the original isoclinal folds.

The axial-plane folding is evident on the accompanying geologic map, FIGURE 2, where both the formation belts and the foliation are shown to swing around the Poundridge granite mass.

East of Titicus Reservoir, the belt of Inwood marble lying between belts of Fordham gneiss is the keel of a double-plunging synclinorium. The synclinorium opens up to the west, south of Titicus Reservoir, and to the east, east of the Connecticut state line. The synclinorium is part of the northwest limb of the large axial-plane fold whose axis extends northeast through the Poundridge granite mass.

The axial-plane folds occur between the Highlands border fault on the northwest and north, and the Siscowit granite fault on the southeast. The writer concurs in Scotford's interpretation (1956, p. 1193) that the axial-plane folds were formed when the pre-existing structures were squeezed between the

Highlands block and the Siscowit granite as the former was thrust upward and outward toward the Siscowit granite.

It should be emphasized that in the area of axial-plane folds, as elsewhere, the Fordham gneiss is conformable with the rest of the New York City group and maintains a consistent stratigraphic and structural position within the group. No evidence has been encountered in the mapping that would indicate that a fault separates the Fordham gneiss from the Inwood marble.

The consistent parallelism between the Fordham and Inwood cannot reasonably be interpreted as a pseudoconformity, as was proposed by Balk (1936, p. 771). The mechanism described by him (1936, p. 732–737) for the origin of pseudoconformities involves severe isoclinal folding and the obliteration of the original unconformity by development of zones of intense shearing. The concept is certainly valid for the areas he describes in Dutchess County, where the Poughquag quartzite has been dragged into pseudoconformable relationship with Precambrian gneisses along major faults. However, the demonstrable stratigraphic characteristics of the Fordham—particularly the interbedding with Inwood and Manhattan formations—preclude faulting as an acceptable explanation for the position of the Fordham in the New York City group. It is scarcely credible, furthermore, that the uniform stratigraphic position of the Fordham gneiss relative to the Inwood marble throughout the known extent of the contact, from New York City to Danbury, Conn., could have resulted from faulting of the gneiss into younger rocks.

Within the Fordham gneiss the foliation and lineations are everywhere consistent with those in the overlying Inwood and Manhattan formations.

The Correlation Problem

Early history. Beginning with Mather's early report on the First Geological District of New York (1843), attempts to correlate the New York City group with the Cambro-Ordovician Poughquag-Wappinger-Hudson River pelites sequence north of the Hudson Highlands has been a recurring theme. Merrill (1890) originally followed Mather's interpretation, but later (1898) he consigned the Fordham gneiss to the Pre-Cambrian and considered the rest of the group to be Ordovician. Berkey (1907) considered the entire group to be Pre-Cambrian, and later suggested it was equivalent to the Grenville series because of similarities in metamorphic lithologies. Knopf and Jonas (1929) correlated the Fordham gneiss with the Baltimore gneiss, which they considered to be Archean. They correlated the younger formations of the New York City group with the supposedly Pre-Cambrian Glenarm series of Pennsylvania and Maryland. This, too, was a correlation based upon similarities of metamorphic lithologies and stratigraphic sequence.

Balk's correlation. Until the publication of Balk's well-known Dutchess County studies (1936) it was widely accepted that the entire New York City group was Pre-Cambrian. Balk believed that only the Fordham gneiss was the equivalent of the Pre-Cambrian gneisses of the Highlands, and that a complex system of arcuate faults brought the underlying Fordham into pseudoconformable contact with the younger formations in the New York City group. These younger rocks he correlated with the Cambro-Ordovician sequence north of the Highlands.

The general high regard for Balk's detailed work on the structural elements and metamorphism of the Dutchess County rocks perhaps accounts for the common but uncritical acceptance of his regional interpretation of the structural and stratigraphic relationship between the two metamorphic terranes.

Balk's interpretation was based principally upon three premises: (1) that the fossiliferous Cambro-Ordovician strata of Dutchess County can be traced continuously through the Wingdale Gap eastward beyond the Pre-Cambrian Highlands into the New York City group; (2) that the New York City group consists of the Lowerre quartzite, the Inwood marble, and the Manhattan formation—a presumed stratigraphic sequence comparable to the Poughquag-Wappinger-Hudson River pelites sequence north of the Highlands; (3) that the Fordham gneiss is the equivalent of the Pre-Cambrian gneisses of the Highlands, and was emplaced into the New York City group by faulting. A discussion of these premises follows.

Wingdale Gap. Balk's equating of schists on opposite sides of the Harlem Valley through the Wingdale Gap may well be valid, and is based upon sound geologic reasoning, although in fairness to the argument it should be pointed out that it is impossible to trace any recognizable schist unit through the Gap. Outcrops are not sufficiently abundant or that strategically located.

In any case, the question of whether cognate units can be carried through the Wingdale Gap has little bearing on whether the New York City group is a correlative of the Cambro-Ordovician Poughquag-Wappinger-Hudson River pelites sequence. The Wingdale Gap is not a gap *through* the Highlands; it is more properly considered a gap *into* the Highlands. The southern end of the Harlem Valley near Towners, for example, is still separated from the nearest New York City group rocks at Brewster by more than five miles of uninterrupted Pre-Cambrian Highlands gneisses. Between the rocks at Wingdale Gap and the northernmost New York City group rocks near Danbury is a terrane composed of noncorrelated metamorphic rocks, including the Hartland and Waramaug formations (Rodgers, 1956). Until the affinities of these rocks are determined, the regional correlation problem must still be considered open.

Lowerre quartzite. Recently Norton and Giese (1957) have called attention once again to the long-standing controversy concerning the so-called Lowerre quartzite in the Manhattan Prong and its part in the important correlation problem of the region.

The name Lowerre quartzite was introduced by Merrill (1898, p. 26) for "... a stratum of thin-bedded quartzite ..." at the base of the Inwood marble and overlying the Fordham gneiss near the old Lowerre railroad station in Yonkers. No adequate description was given by Merrill for the type locality, nor for the other occurrences cited by him. In a later report (Merrill, 1902) he described the Lowerre in general terms for its various localities as "... a quartzite varying from almost white to brown in color; characteristically thin-bedded, occasionally massive, often with muscovite or tourmaline developed along bedding and cleavage planes." Berkey (1907) believed the so-called Lowerre to be "... only an upper quartzitic facies of the basal or Fordham gneiss formation."

I concluded from a study of localities in which the Lowerre has been reported in the literature that the Lowerre quartzite does not exist, and that it has either been erroneously reported, or that strongly sheared phases of the upper part of the Fordham gneiss have been misidentified as quartzite (Prucha, 1956, p. 677–683). Since publication of my earlier report one or two other localities have been called to my attention and some bore-hole data in the New York City area have been noted (Dolgoff and Tuozzolo, 1957).

In their recent note Norton and Giese (1957) reviewed the question of the Lowerre quartzite and concluded that, in fact, a quartzite does exist between the Fordham and the Inwood at a number of places, although its sporadic distribution and rather ambiguous composition are recognized. They suggest that the absence, or apparent absence, of a quartzite almost everywhere between the Fordham and the Inwood could be the "... result of nondeposition, of concealment by glacial or alluvial deposits, of removal by erosion or faulting, or of granitization and cannot be taken as disproving correlation ..." between the New York City group and the Cambro-Ordovician rocks north of the Hudson Highlands. I agree with this view, but concur even more heartily with their conclusion that the stratigraphic significance of any quartzite between the Fordham and the Inwood has been overemphasized.

It is clear that available positive evidence fails to establish unequivocably that a separate, distinct, and recognizable quartzite exists as a stratigraphic entity between the Fordham gneiss and the Inwood marble in the Manhattan Prong; hence, the so-called Lowerre quartzite does not constitute a valid formation in the New York City group. The name Lowerre, therefore, should be used only in the context of historical development of geologic thought in the region where it was conceived. In view of the spurious, or at best doubtful, status of the Lowerre quartzite at the present time, it should not be used as a positive basis of correlation.

The presumed similarity of stratigraphic sequence between the New York City group and the Cambro-Ordovician rocks north of the Hudson Highlands thus fails on several counts to be a valid basis of correlation: first, the Lowerre quartzite is not established as an acceptable equivalent of the Poughquag quartzite; second, the Fordham gneiss is demonstrably an integral part of the New York City group both stratigraphically and structurally, but has no recognizable counterpart in the Cambro-Ordovician rocks north of the Highlands.

Fordham gneiss versus Highlands gneisses. It should be emphasized that the Fordham gneiss is not the equivalent of the undoubted Pre-Cambrian gneisses of the Hudson Highlands. This is demonstrated by the structural and stratigraphic characteristics of the Fordham, but it is also seen in the lithologic dissimilarity between the gneisses.

Fluhr (1945; 1950) was probably the first to point to the distinction between the gneisses. Scotford's recent work (1956), added to my own, has elaborated upon the distinction. To reiterate what has been published elsewhere (Fluhr, 1945, 1950; Scotford, 1956, p. 1160; Prucha, 1956, p. 675), these are the chief lithologic differences between the Fordham gneiss and the Pre-Cambrian gneisses of the Hudson Highlands:

The great persistence along strike of thin, inch-scale mineralogic layers in the Fordham is in contrast to ill-defined, discontinuous layers in the Highlands gneisses.

There is an abundance of relict sedimentary beds in the Fordham gneiss, but a general lack of them in the Highlands gneisses.

The general lack of clinopyroxenes in the Fordham is in contrast to their abundance in the Highlands gneisses.

There is a much less common and less advanced granitization of the Fordham gneiss compared to the Highlands gneisses.

There is an abundance of accessory graphite in the Highlands gneisses, but an extremely sparse distribution of it locally in the Fordham.

There is a greater abundance of sulfides, such as pyrrhotite and pyrite, in the Highlands gneisses, as well as of iron ore minerals, both concentrated and disseminated.

There is a smaller number of granitic intrusions in the Fordham, with a more persilicic composition compared to those in the Highlands gneisses.

The Fordham gneiss, and the rest of the metamorphic rocks of the New York City group, belong to the amphibolite facies, whereas the gneisses of the Hudson Highlands are somewhat higher in grade.

Summary of salient points. It would be well to summarize here those salient points with which any attempted age correlation of the New York City group must be consistent:

The Fordham gneiss is not the equivalent of the Pre-Cambrian gneisses of the Hudson Highlands. It is the conformable basal unit of the New York City group, of which it is an integral and partly interbedded metasedimentary formation. There is no evidence of faulting between the Fordham gneiss and the Inwood marble.

The formations of the New York City group, including the Fordham gneiss, were deformed simultaneously, both in the earlier stage of isoclinal folding and in the latter stage of axial-plane folding. The internal structural elements of the New York City group are consistent among the three constituent formations.

The Cambro-Ordovician sequence north of the Hudson Highlands can not, as yet, be traced through the Pre-Cambrian Highlands directly into rocks of the New York City group.

The stratigraphic sequence of the New York City group is not a recognizable facsimile of the sequence in the Cambro-Ordovician rocks north of the Hudson Highlands. The so-called Lowerre quartzite can not be considered the equivalent of the Poughquag quartzite unless the former can be demonstrated to be a valid formation. In any case, the Fordham gneiss may not be considered apart from the New York City group, and the Fordham has no recognizable counterpart in the Cambro-Ordovician sequence.

Other methods of correlation. In the absence of recognizable index fossils, the age of the New York City group can not be determined directly. Among metamorphic rocks, correlations based upon lithologic similarity are always extremely tenuous, and the present case is no exception. Thus, for example, it is not sound to consider the New York City group to be a possible equivalent of the Pre-Cambrian Grenville series simply because of admitted similarities in lithologic type.

K/A age determinations. The potassium-argon method of age determination makes it possible to measure the time of the latest metamorphic event, but the results of such analyses must be interpreted with a clear understanding of the geologic conditions that exist. At this stage of development in methods of radioactive-age determination it would appear to be a fair viewpoint that, in cases where laboratory age dates are not consistent with clearly demonstrable field relationships, the laboratory dates should not be considered definitive.

In a recent paper, Long and Kulp (1958) report potassium-argon dates of 400 million years (m.y.) and 440 m.y. for biotite from two separate samples of Fordham gneiss collected along the New York Thruway east of Tappan Zee Bridge. These ages contrast with 366 ± 9 m.y. for micas from schist, marble, and pegmatite from the upper formations of the New York City group.

It is suggested cautiously by Long and Kulp, on the basis of these data, that the Fordham gneiss may represent older basement rock that did not lose all of its argon during the 366 ± 9 m.y. recrystallization.

In this particular case, with a stated experimental reproducibility of 4 to 5 per cent, the determined ages of metamorphism of the Fordham and that of the Inwood and Manhattan approach one another closely when minimum possible values of the Fordham and maximum possible values of the Inwood and Manhattan are used. Thus, considering the inherent vagaries in the potassium-argon method, the determined age differences may not be very significant.

It should be noted, too, that satisfactory petrographic criteria are not yet available to make it possible to distinguish partially reconstituted micas from wholly reconstituted ones, or from micas of neomineralization. Hence, without reasoning *ad hoc*, one cannot infer from Long and Kulps' suggested interpretation of the apparent age discrepancy that the Fordham is a Pre-Cambrian gneiss partly reconstituted during the 366 ± 9 m.y. metamorphism of Cambro-Ordovician Inwood and Manhattan formations. It would be just as logical, although still *ad hoc*, to consider the *entire* New York City group to be of Pre-Cambrian derivation, the Fordham being somewhat less reconstituted than the Inwood and Manhattan during the late Ordovician metamorphism.

Conclusion

Inasmuch as we still do not know the age of the original sediments comprising the New York City group, it would appear that we have not progressed very far on the problem in the past 100 years. Whatever headway has been made, however, has come largely from geologic mapping in the field. This approach still has much to offer; indeed, it is a necessary first step to an eventual solution of the problem.

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